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The economics of urban water policy : infrastructure, scarcity, and conservation

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The Economics of Urban Water Policy: Infrastructure, Scarcity, and Conservation

by

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B.A., Economics, Idaho State University, 2003
M.A., Economic Theory, University of New Mexico, 2006

DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Doctor of Philosophy
Economics

The University of New Mexico

Albuquerque, New Mexico

August, 2009

Dedication

To Lisa and the little presidents, Jaxon and Lincoln . . .

Acknowledgments

As economists, we believe that people are driven by incentives. One way to interpret that is, money makes the world go 'round and in our case, research possible. Research grants from the U.S. Department of Agriculture and the American Water Works Association Research Foundation funded me to work on projects where I learned many of the tools that I apply here. Thanks to Mrs. Vivian Boyle for her generosity through the Gerald Boyle Graduate Student Award in Public Finance, the family of J. Raymond Stuart for the Graduate Prize in Economics, and the Graduate Dean of Arts and Sciences for the Dissertation Scholarship. I thank you for your financial support.

The slogan of one of my favorite and most frequently visited websites, Google Scholar, symbolizes my appreciation for the many people who contributed to the success of this dissertation. "Stand on the shoulders of giants" is an expression that describes how I feel about the intellectual giants with whom I have been fortunate to work. These people shaped who I am as an economist and fully equipped me with the tools of the trade. For this, I say thank you to a number of different people.

Kristine Grimsrud, Kate Krause, and Jennifer Thacher taught me to model in detail, to find intuition in results, and to work with rigor in analysis. Bob Patrick and Bruce Thomson taught me to think about how models fit with the real world, which really is just a special case of theory. Janie Chermak, my committee advisor, was instrumental in seeing me to the finish line. I appreciated leaving her office feeling like my equations, tables, and figures were meaningful; a feeling I did not always have as I entered. She helped me see opportunities I otherwise would have overlooked, which let me get more out of graduate school than I ever dreamed possible. She taught me to be an economist, to be committed to excellence, and to go an epsilon (or two) beyond what I thought was my best performance. Thank you for your mentorship and friendship, and to the committee, and for the hours you spent reviewing my work. To these intellectual giants I say thank you for five years of standing on your shoulders. You're welcome at my campfire anytime!

Tesa Stegner, Stu Burness, and Phil Ganderton are other intellectual giants to whom I say thank you although they were not on my committee. Tesa, my undergraduate advisor, rescued me from career uncertainty by starting me on the path to become an economist. Thank you for your effort. Stu taught me how to be a teacher, critical thinker, and most importantly, to ask the question: "Is it tractable?" What I thought was misfortune at Stu's UNM T not corresponding to my own turned out not to be the case since I could replay in my mind our many visits, drawing upon them to determine if my latest model would find his approval. I could simply ask myself: “Is it tractable?” Phil gave me a perl of wisdom that I frequently use. I will forever look at a piece of research, asking myself in a way only Phil could: “What the . . . ?” I take from him the importance of making research count, for telling the reader why they should read beyond the introduction. To these researchers, I too say thank you.

Thanks to my cohort colleagues for helping with research, experiments, and working out modeling details, especially my office mates. Steve Archambault’s inquisitiveness and Rohnn Sanderson’s time-series expertise helped strengthen my research. Their questions and suggestions were great and provided valuable contributions. I wish them success in their pursuits, academic or otherwise.

A good support system is a necessary condition to graduate school success. A candidate needs ‘people’ to get through this process. My friends and family filled that role for me. Mark Bastian and Doug Weitzel provided support, encouragement, and diversion in the form of excellent adventures: some New Mexico back country, some Albuquerque urban. Doug and Mark helped me achieve a stable equilibrium that at many points felt very unstable. They will never know how much that meant, you have my heartfelt thanks! My children’s grandparents, Eric and Janis Hansen and Gary and Linda Larsen, provided a great deal of support from the beginning. Phone calls, visits, and interest in my success played a key role in getting through some really tough times. I say thank you to ‘my people’ because without their support, I am sure the steepness of trail would have rendered it impassible.

I dedicated this dissertation to my wife Lisa and to our children, Jaxon and Lincoln, since the completion of this work is not only mine but theirs too. They followed me on the emotional, sinusoidal wave that a candidate travels on the way to the end of graduate school. They learned first hand, by experience, the opportunity cost of graduate school; they sacrificed more than they know so that I could pursue a professional goal. However, Lisa knows the cost. I am forever thankful for her and her love and support. I look forward to showing her and the little presidents that graduate school does pass a benefit-cost test, that the effort really is worth it. Thank you guys for your willingness to go on this adventure!

Finally, I am grateful for the Hand of Providence whose glory is intelligence. He blessed me with the angels that I mention here so that I could increase my intellectual capacity. These people, spiritual strength, and countless other blessings made possible my ability to finish this dissertation, I am eternally grateful.

The Economics of Urban Water Policy:

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ABSTRACT OF DISSERTATION

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Abstract

This research focuses on urban water policy. The three papers extend the literature through economic application, taking theory in a direction that informs water resource managers on optimal decision-making or a better approach to management. Three primary results are: first, that the optimal infrastructure investment path is impacted by existing capital stock, water policy, and the size of the customer base served. Second, optimally managed, optimally priced urban groundwater mitigates aquifer drawdown and generates excess revenue that may be used for capital investment. Third, to achieve water conservation through non-price methods, managers should use a neighborhood, community-organized approach.

Water systems across the United States need money for infrastructure repair and replacement. Utility level investment needs are grounded in existing infrastructure that is nearing the end of its economic life in a time of unparalleled population growth, suggesting that optimal investment should reflect the same. Chapter 2 presents a model that develops the optimal investment decision and uses two-stage least squares to test it. Consistent with model predictions, the empirical results show how the effects of population, capital, and existing policy influence infrastructure investment. The estimates indicate that per capita stock has a lagged impact on per capita investment and that increasing new customer connection costs reduces investment need more than increasing water rates to existing customers.

Western U.S. water supplies are increasingly scarce due to, among other things, population growth and climate change. These two realities imply that increased scarcity may lead to over-consumption, premature resource exhaustion, and shortages. Chapter 3 develops a hydro-economic model of social welfare maximization constrained by water availability. The model provides optimal water use and the efficient price. A dynamic simulation model suggests that, for Albuquerque, New Mexico, current water prices are 20 percent of the price level that includes scarcity value. Investing the scarcity value in water infrastructure is one way to overcome regulatory pricing barriers and allocate water efficiently thus solving two problems with a single policy-prescription.

Scarcity requires residents of arid, heavily populated regions of the U.S. to increase water conservation or face the consequence of shortfalls. As an impure public good, conserved water is subject to free-riding behavior. Chapter 4 considers a demand side, non-price management alternative to promote water conservation. Using experimental economics, this paper explores the extent to which community interaction impacts consumption. In a context rich, induced value environment participants are asked to allocate water between their group's public source and private use. Three

treatments vary group size, information, and communication to simulate actions a water manager could take to promote conservation. The results show that small group size and communication promote conservation, but the role of information is mixed.

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Glossary

2SLS	Two-stage-least-squares econometric regression
ABCWUA	The Albuquerque Bernalillo County Water Utility Authority
AWWA	American Water Works Association
CIP	Capital Improvement Project
CPR	Common Pool Resource
DR	Decision Ratio of private water use decision to individual optimum
EPA	U.S. Environmental Protection Agency
MC	The marginal cost of pumping water from a groundwater aquifer
MNB	Marginal Net Benefits of infrastructure investment or repair
MPCR	Marginal Per Capita Return
MUC	The marginal user cost, the marginal cost place on all future water users for an acre-foot of water used in the current period.
OCM	Optimally controlled groundwater management, the solution to the water scarcity model.
OLS	Ordinary least squares econometric regression

SQM	The Status-Quo management alternative, the comparison case for OCM.
UNM	University of New Mexico
USGS	United States Geological Survey
WIN	Water Infrastructure Network

Chapter 1

Urban Water Policy

Urban water policy makers in the western United States face a predicament from uncertain futures on three fronts. These include ageing water infrastructure, increasing demand for water in multiples uses, and more frequent and more intense occurrence of drought. Aging water infrastructure implies the replacement costs will be substantial and come due within the next 30 years (Cromwell et al., 2001). Population demographics, different from which water infrastructure was originally designed to serve, implies that system expansion will be needed. Meeting the supply challenges of a growing population proves problematic for systems in arid climates struggling to meet the water needs of existing populations. These, coupled with reduced water supplies, have water managers asking the question, "Can we have it [scarce water resources and population growth] all?"[1] Managers are thus left with a balancing act between water scarcity and population growth fueled by economic expansion.

This research contributes to the water resource and economics literatures through

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[1] For example the Arizona Hydrological Society and Southwest Hydrologists recently held a symposium; "2007 Regional Water Symposium, Sustainable Water, Unlimited Growth, Quality of Life: Can We Have It All?" Tucson, Arizona, 30 August 2007, to address such issues.

three research papers. The first paper, Chapter 2, develops a path of optimal water infrastructure investment by extending the existing infrastructure literature to specifically address water infrastructure. It applies the capital accumulation model from the macroeconomics literature to reveal the optimal, water infrastructure investment path. Chapter 3 presents a model for the optimal extraction of scarce, groundwater resources given a population growth rate and then postulates the extent to which charging water's scarcity value defrays the investment gap. This paper extends the groundwater management literature by applying a model that was first used to investigate water policy for agriculture. The results extend the understanding of scarcity priced water by showing the extent to which aquifer drawdown is mitigated. Chapter 4 explores the customer's water consumption–conservation decision in an experimental context using treatments an urban manager may implement. The findings extend the experimental economics literature by adapting the standard public goods framework to allow for conservation. This extends the water management literature since it suggests a new approach to achieve water conservation.

The sections that follow here provide a summary of the research in each paper. These sections outline in more detail the need for better, more efficient water policy pertinent to the three areas of focus. The methodology is discussed followed by a summary of the results.

1.1 Infrastructure

One challenge to on water resources managers is from antiquated infrastructure. Distribution and transmission mains that were placed into service as long ago as the end of the nineteenth century are now at the end, or will soon reach the end, of their economic usefulness. Old pipes, made of cast iron, steel, and reinforced concrete are speckled with leaks which create water loss and lead to deleterious health effects.

Estimates of annual U.S. water loss from leaking pipes reach as much as 1.7 trillion gallons. That is enough water to supply a city of 25.9 million people for an entire year (EPA, 2007).[2] Further, the loss in water pressure due to leaks has been linked to gastrointestinal illness since low water pressure reduces water quality by increasing the potential for contamination (EPA, 2007).

Failing water infrastructure is part of a larger U.S. infrastructure problem. The American Society of Civil Engineers periodically reviews the state of U.S. infrastructure. In the 2009 report, drinking water infrastructure was given a 'D-' grade (ASCE, 2009). No other infrastructure type ranked lower. In part, this is due to water infrastructure that has not needed replacement since pipes were installed with sufficient quality that only now are they wearing out. Now, pipes across the U.S. need to be replaced leading some to call the next 20 years the "Dawn of the Replacement Era" (Cromwell et al., 2001). Others have estimated the size of capital investment needed to replace failing U.S. water infrastructure at $23 billion annually and a cumulative total of up to $2 trillion by the year 2019 (WIN, 2000a,b). Failing water infrastructure is problematic since the breadth of general, U.S. infrastructure failure means that Federal assistance at the local level may be limited. This leaves water infrastructure challenges to be dealt with at the utility level.

To date, the economics literature has treated water infrastructure as a subset of social infrastructure which includes energy, schools, and transportation. As water infrastructure needs increase, the economics literature on water infrastructure will continue to burgeon, a field to which Chapter 2 contributes. Optimal water infrastructure investment, modeled at the level of a water utility, sheds light on which factors influence the investment decision in terms of exogenous parameters and variables that a water resources manager may control. The model thus informs water resource managers how to approach a more optimal path of infrastructure

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[2] This assume 180 gallons daily per capita consumption.

investment. This research fits with the Best Management Practices that the U.S. Environmental Protection Agency identifies as one of four in the Sustainable Water Infrastructure Initiative (EPA, 2006) since it provides managers information on better infrastructure management.

Chapter 2 develops a model that uses optimal control theory to set up a water utility's investment decision. The utility's infrastructure investment decision is one that minimizes utility costs.[3] The model explicitly considers exogenous input and output costs with endogenous changes in system capacity and investment. Investment, the control variable, is optimally chosen over a fixed time horizon. The theoretical model produces four noteworthy results. The optimal investment decision is a function of three effects: the population effect, the capital stock effect, and the policy effect. Moreover, the model illustrates that infrastructure investment is costly to the utility, that there is an opportunity cost of investment which the utility must consider on the optimal path. I use a two-stage least squares econometric estimation to test the theoretical model.

The empirical model relies on data from the American Water Works Association (AWWA), which conducts the Water and Wastewater Rate Survey (AWWA, 2004, 2006). The AWWA surveys water and wastewater systems in the U.S. and 29 countries concerning such things as utility costs, system characteristics, and water system needs. I use the data, from survey years 2004 and 2006, to validate the model. The theoretical model does not control for characteristics that may vary widely for systems outside of the U.S. Thus, the empirical model uses data from the 248 U.S. water systems in the surveys.

I construct six empirical test that compare the theory and empirical models. Five tests indicate that the theoretical model is consistent with the empirical model, which suggest that theory model implications provide managers information to move

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[3] The model maximizes profits since by duality that is analogous to cost minimization.

to more optimal infrastructure investment. Three effects are numerically estimated. The population effect suggests that a one percent increase in population leads to a 2.2 percent increase in investment need. The capital stock effect is the reverse of population; for a one percent increase in system capacity, investment need falls by 2.2 percent. The policy effect shows that increasing water prices on existing rate payers may increase investment need while increasing connection costs may reduce investment need. This result informs policy makers of where the burden of expansion should be placed; it is more efficient for new connected customers to pay the expansion price.

Chapter 2 contributes to the economics literature as it expands the horizon of the social infrastructure research line. The research contributes to the water resources literature since it informs policy makers of factors that may help water resource managers move to more optimal infrastructure investment. Identifying factors that affect the optimal decision may allow managers to mitigate investment shortfalls thus bridging the gap between actual and needed investment.

1.2 Scarcity

A second challenge for water resource managers is increased scarcity. In a recent summary of global climate change studies, Saunders et al. (2008) find that temperature increase in the U.S. West is greater than in any other part of the country. The average temperature increase is 1.7 degrees Fahrenheit but there is variation across the West, which ranges from 2.4 in the mountain states to 2.7 in the Southwest. The most notable, however, is Nevada where the increase is 3.6 degrees closely followed by Colorado at 3.1 degrees. This is of particular concern in light of two points.

First, in a forthcoming report on climate change impacts to the Colorado River, Barnett and Pierce (2009) find that by 2050, Colorado runoff will decline by up to 20 percent. This means that nearly 90 percent of scheduled water deliveries, distributed across seven Western states, will be missed. The second point of concern is that the arid climate, where water scarcity is greatest, is the same region with the greatest forecasted population growth. The U.S. Census Bureau estimates a 30-year change in population in the U.S. West at 46 perecent; in Nevada alone the change is 114 percent. Through the first half of this century, people living in the West are going to have to make do with less. There simply is not enough water to support existing water use leading Barnett and Pierce to conclude that the Colorado River is no longer sustainable. The Colorado example illustrates that U.S. Westerners will have to undergo a paradigm shift in their approach to water use or else face shortfalls.

Chapter 3 proposes that one way to deal with increasing water scarcity is to optimally control groundwater pumping in an urban environment. From the perspective of social welfare maximization, the model finds optimal water pumping. Water availability, measured by water table height, constrains the social welfare function. The model addresses the extent to which controlled pumping may reduce aquifer drawdown and generate revenue for infrastructure investment. Thus, controlled pumping provides a water manager with a “two-for-one” solution to water scarcity and failing infrastructure.

The methodology of the chapter is to use a theory and empirical model. The solution to the social welfare maximization is a system of differential equations, one of which is the path of optimal water pumping. The empirical model, a dynamic simulation, evaluates the effectiveness of controlled groundwater pumping at mitigating aquifer drawdown. The simulation requires specific functional forms for water demand and water utility production costs. I econometrically estimate these, apply the model to Albuquerque, New Mexico, and simulate the model over a 40-year time horizon on a monthly time step.

I estimated the model with data from the Albuquerque Bernalillo County Water

Utility Authority. The data is of total revenue and total water production across the utility for 1994 through 2004. I use the econometric parameter estimates, aquifer height data, and population data to initialize the simulation model. Aquifer height data is from the U.S. Geological Survey for a monitoring site near the center of Albuquerque. The population data is from the Bureau of Business and Economic Research at the University of New Mexico. Prior to running the simulation model, I calibrate it to existing aquifer height and population data such that the model replicates the raw data.

A management type that increases price at the rate of inflation serves as a reference to which I compare controlled groundwater pumping; I assume three percent inflation. I find that the controlled pumping solution preserves 21.6 feet of aquifer height at the terminal time over the alternative. The simulated population uses 522 acre-feet less per month under the controlled pumping approach. The results are sensitive to the population growth rate. The base case population growth rate is 1.2 percent; a one-half percent growth rate leads to a seven foot difference in aquifer height and a three percent growth rate leads to a difference of 64 feet.

Controlled groundwater pumping maps into a path of optimal water prices. The mapping reveals a marginal user cost, which is the opportunity cost of foregone water use. That is, it is the cost borne to users in all future periods because of water used today. I find that current water prices are 20 percent of the level that reflects the marginal user cost. This information is useful for water managers who wish to set water prices to reflect the scarcity value of the resource and thus use it efficiently. Further, charging the scarcity value generates significantly greater profits at the end of the time horizon than the alternative. The implication is that charging water prices that reflect the scarcity value mitigate aquifer drawdown and produces revenue, which a manager may use for infrastructure investment.

These results do not allow me to speak to an optimal population growth rate.

However, they do suggest that for managers who have to manage an increasingly scarce resource concomitantly to major changes in population, prices that reflect the marginal user cost significantly preserve the resource. Scarcity pricing generates revenue with which infrastructure repairs may be addressed. A water resource manager thus has a “two-for-one” solution to water scarcity and infrastructure failure by simply charging a water price that reflects the marginal user cost. The economists’ long-sounding battle cry for increased water prices is justified; marginal user cost pricing successfully signals scarcity.

1.3 Conservation

Increased water scarcity means that, in addition to efficient water prices, resource managers may need additional tools to achieve water sustainability thus meeting multiple water demands. Urban water managers have to reconcile the fact that there are environmental, recreational, cultural, and agricultural entities that have water demands contemporaneous to residential customers. For water that is allocated for urban use, excess can then be thought of as a public good since it may be used in one of these alternative purposes or saved for future generations. To the urban user, conserved water becomes a public good since foregone use produces a benefit the consumer may experience in ways other than consumption.

Chapter 4 models the water consumption decision of a residential customer in a public goods framework. The model simulates a hypothetical surface water allocation to urban users. The research question is: to what extent do community factors matter in the water use decision? That is, how do neighbor interaction, information, and group size impact consumption behavior? To answer this question, this paper applies experimental economics and treatments that an urban water manager may use as additional conservation-promoting mechanisms. Group size, information, and communication are experiment treatments that parallel demand side, non-price management tools.

The model is tested experimentally using a protocol adapted from the voluntary contributions mechanism (Isaac and Walker, 1988a,b; Isaac et al., 1994). The protocol is a voluntary conservation mechanism. In it, the public good is water allotment to the group called the "Public Water Bucket." Participants are asked to determine how much of the public bucket they would like to place in their "Private Water Bucket." Participants have handouts that show the payment amount for public and private bucket units. The public bucket payments are identical but there are three versions of the private bucket handout. This simulates three water use types; high, medium, and low. Consumer type high has more value in private consumption than the medium type who in turn has more value in private consumption than the low player type. The protocol does not control for temporal effects since the experiment is in a single-stage framework.

The three treatments, group size, information, and communication parallel management tools a water manager may implement. The group size treatment sheds light on the issue of how conservation is best targeted, at a local neighborhood level or city-wide level. The information treatment anonymously informs the group members about the consumption decision of all other players in the group. The communication treatment lets participants communicate with other group members anonymously by writing on a group discussion board, which simulates a newsletter or other mechanism a manager could use. The experiments are populated with participants from the English speaking, adult, Albuquerque, New Mexico population. Participants are students from the University of New Mexico (UNM) and Albuquerque residents. All experiments were conducted in classrooms in the Department of Economics at UNM.

The results from the group size and communication treatments indicate that a small group size where communication is present promotes a lower water consumption decision than otherwise. The role of information is mixed; in the large group participants' water consumption tended to increase but decreased in the small groups. These results are significant since they suggest that an organized, neighborhood approach to water conservation may be more effective than city-wide encouragement. The organized community approach found here is thus another possible tool policy makers may use on the path to promoting water sustainability.

Chapter 2

Optimal Water-Utility Infrastructure Investment

2.1 Introduction

A gift from previous generations, public water-infrastructure is reaching the end of its useful economic life in cities across the United States. Infrastructure placed into service following the population booms of the 1890s, 1920s, and 1950s has one thing in common: it will need to be replaced within the next 30 to 40 years (Cromwell et al., 2001). A forthcoming report by the American Society of Civil Engineers highlights this reality with the 'D-' grade assigned to water infrastructure (ASCE, 2009). Infrastructure investment needs are directly related to conditions of existing infrastructure and population size. This paper characterizes optimal infrastructure investment, at the level of the water service-providing utility, in terms of population size and capital stock. I model the infrastructure investment decision as a function of the customer base and the capital stock.

Water-infrastructure has been addressed previously in the economics literature as a subset of social-infrastructure, which typically includes transportation, structures, equipment, and water systems (Munnell, 1992). Social-infrastructure research has primarily investigated the returns to infrastructure investment as a share of GDP (Munnell, 1992; Gramlich, 1994; Rauch, 1995; Pereira, 2000). The seminal investigation (Aschauer, 1989), hypothesized that the lack of social-infrastructure investment may have played a role in the U.S. productivity decline of the 1970s, a result later confirmed by Munnell (1990). Cummings et al. (1978) looked at the effect of social-infrastructure on wages finding that people are willing to trade off a reduction in wages for an increase in per capita social-infrastructure stock. The U.S. Bureau of Economic Analysis estimates that the value of U.S., non-military infrastructure is $3.54 trillion dollars.[1] Munnell (1992) found that of this total, the asset value of water and sewer systems constituted 14 percent or $495.6 billion dollars. This result is consistent with time series analysis by Pereira (2000) who found that water infrastructure investment as a share of aggregate public investment averaged 16 percent over the time period 1956 through 1997.

Existing water-infrastructure is nearing the end of its useful economic life. Technical studies estimate the water-infrastructure replacement bill as an emerging gap between existing investment and projected investment need. The Water Infrastructure Network (WIN) estimates the investment need, for systems to meet guidelines of the Clean Drinking Water Act and Safe Drinking Water Act, at $23 billion dollars annually above current investment (WIN, 2000a). The U.S. Environmental Protection Agency (EPA) estimates that this gap ranges between $485 billion and $896 billion dollars over the period 2000 through 2019, the WIN estimates are as high as $2 trillion dollars over the same period (WIN, 2000b; EPA, 2002b). These three studies note that both infrastructure age and the size of the population served increase

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[1] The original estimate, from unpublished data at the U.S. Bureau of Economic Analysis in 1991 dollars was $2.2 trillion dollars. Estimate converted to 2008 dollars using `bls.gov` inflation calculator.

the magnitude of the gap.

To summarize, 16 percent of public investment maintains US water-infrastructure that valued as an asset is worth \$485.6 billion dollars, the asset is about to reach the end of its economic usefulness, and population growth is significant.[2] The combination of these factors creates a water-infrastructure investment gap of enormous proportion. Assuming Pereira's estimate remains constant implies that projected needs are as much as four times greater than the existing infrastructure asset value.

While the extant economic literature addresses the value of public-infrastructure and looks at the share of water-infrastructure to the total, there has been little research addressing this multi-billion dollar shortfall. Technical reports estimate the size of water-infrastructure needs across the U.S. and Cummings and Schulze (1978) modeled optimal investment for social-infrastructure in boomtowns; however, the literature does not yet address the water-infrastructure investment decision. This research begins to fill that gap by developing a theoretic model for replacement. I model optimal water-infrastructure investment as a function of existing capital infrastructure and the size of the customer base.

The model is a function of utility costs, the price of water, the customer base, and the capital stock. The theoretical model suggests that the utility needs to compare the marginal net benefits (MNB) of continued maintenance to the MNB of replacement. This comparison is conceptually consistent with Nessie Curve Analysis, a method currently used by many water utilities to forecast infrastructure replacement needs (Cromwell et al., 2001). The empirical estimates of the population elasticity and the capital stock elasticity suggest that the size of the existing capital stock and the utility's customer base influences that fundamental economic decision. I find that the water utility may reduce investment need through use of appropriate policy

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[2] The U.S. Census Bureau estimates that through 2020, population growth in the Southern United States to be 43 percent while in the Western U.S. to be 46 percent; `www.census.gov` last accessed 18 April 2009.

tools.

The paper proceeds with theoretical model development in Section 2.2. Theoretical solutions are econometrically tested and discussed in Section 2.3. I use the model and empirical results to consider implications for utilities under various conditions in Section 2.4. The model results offer some conclusions and implications for future work that are discussed in Section 2.5.

2.2 Optimal Infrastructure Investment

The term water-infrastructure covers many components. Distribution systems, water reservoirs, transmission mains, treatment facilities, pumping stations, groundwater wells, and others collectively compose water infrastructure. Water system needs encompass all of these specific infrastructure types. My purpose is to model a general path of infrastructure investment the water utility may follow to address infrastructure needs. Thus infrastructure is a general reference in this paper.

Infrastructure quantity and quality determine the firm's capacity, this implies that the firm may consider infrastructure needs in capacity terms. Capacity needs increase with the customer base and decrease with non-usable infrastructure. The utility's water-infrastructure is really the capital used to treat and distribute water. Thus, a capacity adjustment – adjustment cost model facilitates the firm's capacity adjustment and capital accumulation problem (Caputo, 2005, p. 460).

Capital accumulation models were first used by Gould (1968) who set forth the basic idea to optimally choose capital accumulation at the level of the firm. Prior to Gould, capital accumulation was primarily dealt with in the macroeconomics literature in the tradition of neoclassical growth (Atsumi, 1965; Cass, 1965). More recently, adjustment cost models have been used in the context of natural resources (Rubio,

1992) and water, where Carey and Zilberman (2002) specifically investigate the effect of uncertainty on capital accumulation. This paper contributes to the research on capital accumulation and social infrastructure investment with a direct application to optimal water-infrastructure investment in the water-resources literature.

2.2.1 The Utility's Decision

Consider a publicly owned cost-minimizing water utility. Let the utility be a price taker meaning that a regulatory authority or policy maker and not the firm sets the water price p. Water production $Q(t)$ at any point in time is a function of existing capital, $K(t)$, labor $L(t)$, and capital infrastructure investment, $M(t)$. The utility's production function is:

$$Q(t) = F[K(t), M(t), L(t)]. \tag{2.1}$$

Under the objective of cost minimization, the problem for the firm is to choose an optimal level of investment $M^*(t)$. The firm needs $M(t)$ to replace worn out existing capital and expand capital to meet the demand of a growing customer base. Consistent with economic theory, $F_K > 0, F_{KK} \leq 0, F_L > 0, F_{LL} \leq 0$. The theory of the adjustment cost model says that $F_M \leq 0$, and $F_{MM} \leq 0$. This critical assumption means that instantaneous investment does not produce instantaneous output. For example, a water main built in the current time period does not contribute to water output in the same period.

I model the population effect through the utility's production decision as it enters capital and investment in per capita terms. Assume homogeneity of degree one in the production function. Let

$$F[\mu K(t), \mu M(t), \mu L(t)] = \mu[K(t), M(t), L(t)] \;\; \forall \;\; \mu > 0. \tag{2.2}$$

Given, $L(t) > 0$, let $\mu = L(t)^{-1}$, $k(t) = \frac{K(t)}{L(t)}$, and $m(t) = \frac{M(t)}{L(t)}$. Substituting this into equation (2.2) and assuming that the production function is multiplicatively separable in labor yields

$$f(k(t), m(t), 1) = L(t)^{-1}F[K(t), M(t), L(t)], \tag{2.3}$$

so that

$$F[K(t), M(t), L(t)] = L(t)f(k(t), m(t), 1). \tag{2.4}$$

The right-hand-side ("rhs") of equation (2.4) is the population-weighted production function in per capita terms.

Investment, $M(t)$, in any period impacts the utility's capital stock, $K(t)$, as does the rate of depreciation, δ, of existing capital. That is,

$$\dot{K} = M(t) - \delta K(t), \tag{2.5}$$

where δ is the rate of physical depreciation on the capital stock (Burness and Patrick, 1992). Dividing equation (2.5) by $L(t)$ yields

$$\frac{\dot{K}(t)}{L(t)} = m(t) - \delta k(t). \tag{2.6}$$

Note that the rhs of equation (2.6) captures the population effect while the left-hand-side ("lhs") does not. Further, note that the population-weighted level of capital is $K(t) = k(t)L(t)$. Differentiating this with respect to time and rearranging yields,

$$\frac{\dot{K}(t)}{L(t)} = \dot{k}(t) + \eta k(t), \tag{2.7}$$

where $\eta = \frac{\dot{L}(t)}{L(t)}$. Equating equations (2.6) and (2.7) with rearrangement yields:

$$\dot{k}(t) = m(t) - (\delta + \eta)k(t). \tag{2.8}$$

Incorporating the population effect suggests that the change in the per capita capital stock [$\dot{k}(t)$] is equal to per capita investment [$m(t)$] less depreciated capital. The augmented depreciation term $(\delta + \eta)$ captures the fact that while capital depreciates at the rate δ, the population growth rate η also contributes. Thus the population effect, through augmented depreciation $(\delta+\eta)$, increases the rate at which the capital stock wears out. The population effect captures the fact that more users in the system increases the rate at which infrastructure wears out. Essentially population growth adds to the rate at which capital stock quantity or quality declines. In steady state, per capita investment $m(t)$ equals the augmented depreciation of capital $(\delta + \eta)k(t)$.

The water utility is restricted in what it can optimally choose. For example, population size and the population growth rate are exogenous to the infrastructure investment decision. It can, however, choose an optimal level of capital investment. Therefore the objective for the publicly owned water utility is to optimally manage infrastructure assets, minimize costs, and choose the optimal level of per capita investment, $m(t)$. I model the duality to cost minimization; a firm that minimizes costs given appropriate constraints maximizes profits.

Investment is not costless and comes at a price of g dollars per-unit of capital investment. By choosing investment, the utility replaces failed infrastructure and expands capacity to accommodate a growing customer base. The utility charges the policy regulated water price p dollars per water unit. The parameters g and p constitute the policy effect since the regulator can charge g to new customers connecting to the system and p to current water users. Repair costs to maintain existing capacity are c dollars per capacity unit. The utility anticipates that the labor force growth follows the logistic equation $L(t) = L(0)e^{\eta t}$ where η is labor force growth rate which is, by assumption, the same as the population grows rate. The utility internally discounts profits at the rate ρ to bring benefits and costs of the investment decision into present value dollars.

Formally the utility's objective is:

$$\max_{m(t)} V = \int_0^T e^{-\rho t} L(0) e^{\eta t} \left[pf(k(t), m(t), 1) - ck(t) - gm(t) \right] dt. \tag{2.9}$$

Setting the constant $L(0) = 1$, the objective becomes

$$\max_{m(t)} V = \int_0^T e^{rt} \left[pf(k(t), m(t), 1) - ck(t) - gm(t) \right] dt, \tag{2.10}$$

where $r = \eta - \rho$ and $r < 0$ for $\rho > \eta$, and constraints are:

$$\begin{aligned} \dot{k}(t) &= m(t) - (\eta + \delta)\, k(t) \\ k(0) &= k_0, \underline{k} \leq k(t) \leq \overline{k} \\ \lambda(T) = 0, \quad k(T) &= k_T, \quad T \text{ fixed} \end{aligned} \tag{2.11}$$

which means that the utility would follow the investment path given as the solution to this problem over the planning horizon T. The utility's problem is to choose $m(t)$ (control variable) to maximize utility profits under the constraint of $k(t)$ (state variable) through time and by restrictions on capital given by the boundary conditions. The per capita level of capital must be maintained at a level contained in the interval $(\underline{k}, \overline{k})$.

The current value Hamiltonian is:

$$H = pf\left(k(t), m(t), 1\right) - ck(t) - gm(t) + \lambda(t)\left[m(t) - (\eta + \delta) k(t)\right], \tag{2.12}$$

where $\lambda(t) = e^{rt}\sigma(t)$, is the option value of capital investment. The first order necessary conditions are:[3]

$$\frac{\partial H}{\partial m} = 0 \Leftrightarrow pf_m - g + \lambda = 0 \tag{2.13}$$

$$-\frac{\partial H}{\partial k} = \dot{\lambda} - r\lambda \Leftrightarrow \dot{\lambda} = -pf_k + c + \lambda(\delta + 2\eta - \rho) \tag{2.14}$$

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[3] Note that from here on time arguments will be dropped for ease of mathematical expression.

$$\frac{\partial H}{\partial \lambda} = \dot{k} \Leftrightarrow \dot{k} = m - (\eta + \delta)k \tag{2.15}$$

with the transversality condition,

$$\lim_{t \to T} e^{rt} H(k, m, \lambda) = 0. \tag{2.16}$$

Closed form solution to this problem requires additional functional restrictions. Notwithstanding, some qualitative insights are possible at this level of generality.

Application of the maximum principle produces equation (2.13). Consider first the interpretation of pf_m, the marginal revenue product of investment. Recall that the adjustment cost model assumes $f_m \leq 0$. This implies that investment is costly to the utility in terms of foregone production. Resources allocated to investment in current periods are resources that are not part of profits since instantaneous investment does not produce instantaneous revenue. Thus, pf_m is foregone marginal revenue from investment or in other words, it is an *opportunity cost* of investment. Resources invested in capital are resources not available for other purposes. This underscores the management reality that the utility's investment decision implies tradeoffs. The utility must answer the question, what is the best use of resources? Is it infrastructure investment or alternative investments?

The efficient answer to that question is aided by the costate variable λ, which is the marginal value of investment. Investment is costly yet the utility invests to replace and expand capital as is economically efficient. Expansion and replacement increase the level of asset quantity and quality with which the utility delivers water service to customers currently and in future periods. Thus, λ is an option value since it is the marginal increase in the utility's profit function from an increase in the per capita stock.

For the utility to efficiently choose investment it must choose an optimal per capita level m^* such that the marginal benefits of investing in the system are equal to the marginal costs of investing. The marginal costs are the per-unit cost g, plus the opportunity cost of investment pf_m. Optimally the utility should invest to the point where, rearranging from equation (2.13), the marginal investment benefit is equal to the marginal investment cost,

$$\lambda = g - pf_m. \tag{2.17}$$

To determine whether or not the transversality condition in equation (2.16) is satisfied, consider equation (2.14). At the terminal time T the condition $pf_k = c$ must hold. This says that the marginal revenue product of existing capital is equal to the cost of maintenance. Further, let (k^*, m^*) be the solution to the utility's maximization problem. Assuming $m^* > 0$, and that $\lambda(T) = 0$ so that no value of investment remains beyond the planning horizon, equation (2.17) says that at the end of the planning horizon, the value of the marginal revenue product of investment is equal to the per unit marginal cost of investment. From equation (2.12), total revenue is equal to total cost. Allowing the utility to earn normal economic profits is analogous to cost minimization and is thus a welfare maximizing solution. Therefore, the transversality condition is satisfied.

The utility needs the path of investment that minimizes utility costs over time. The optimal investment path is found by taking the time derivative of equation (2.17) to get:

$$\dot{\lambda} = -p\left(f_{mm}\dot{m} + f_{mk}\dot{k}\right). \tag{2.18}$$

Substituting equation (2.17) into equation (2.14) and equating equations (2.14) and (2.18), with rearrangement, solves for the optimal path of investment.

$$\dot{m} = -\frac{1}{pf_{mm}}\left[-pf_k + c + (-pf_m + g)(\delta + 2\eta - \rho) + pf_{mk}\dot{k}\right]. \tag{2.19}$$

To model the impact of the capital stock on investment, substitute equation (2.15) into equation (2.19) to find the reduced form of the optimal time path for investment,

$$\dot{m} = \frac{[pf_k - c] + [(\delta + 2\eta - \rho)(pf_m - g)] - [pf_{mk}(m - (\eta + \delta)k)]}{pf_{mm}}. \tag{2.20}$$

Combining this with the change in capital stock yields a system of differential equations that can be used to solve the utility's dynamic optimal investment decision:

$$\dot{k} = m - (\eta + \delta)k. \tag{2.21}$$

The utility's investment decision is a dynamic decision based on the population effect, the capital stock effect, and the policy effect. Positive or negative investment is determined by the interaction of the MNB of repairs, the MNB of replacement, and the capital stock effect.

2.2.2 Interpreting the Investment Decision

From equation (2.20), let $[pf_k - c] = \mathrm{A}$. This is the MNB of repair to existing infrastructure. Recall that $[pf_k - c] \geq 0$ since a prudently managed utility would not spend money on repairs if the cost of doing so exceeds the benefits. Thus A dampens the path of optimal investment since $pf_{mm} < 0$.

Let $[(\delta + 2\eta - \rho)(pf_m - g)] = \mathrm{B}$. From equation (2.17) we know that $(pf_m - g)$ is the marginal cost of investment. On the optimal investment path marginal cost is equal to the marginal benefit of investment, λ. The term $(\delta + 2\eta - \rho)$ is the sum of augmented depreciation and the discount rate. Since $pf_{mm} < 0$, B is positive when $(\delta + 2\eta - \rho) < 0$ and negative otherwise. Thus, determining the sign of the MNB of investment is an empirical question.

Let $[pf_{mk}(m - (\eta + \delta)k)] = \mathrm{C}$. This is the capital stock effect modeled through changes in $\dot{k}$. The value of the marginal revenue product of investment with respect

Table 2.1: Summary of Impacts on Optimal Investment $\dot{m}$

	$\dot{k} < 0$	$\dot{k} > 0$	$\dot{k} = 0$
$\dot{m} < 0$	A > (B+C)	(A+C) > B	A > B
$\dot{m} = 0$	A = (B+C)	(A+C) = B	A = B
$\dot{m} > 0$	A < (B+C)	(A+C) < B	A < B

to capital $[pf_{mk}]$ is negative, so the capital stock effect is inversely related to optimal investment.

A summary of possible cases for $\dot{m}$ is given in Table 2.1. The sign of C is the opposite sign of $\dot{k}$; thus, optimal investment is considered under the three possibilities. For $\dot{m}$ to be positive (negative), m must be greater (less) than the rate at which the capital stock wears out.

The second column of Table 2.1 shows that if the change in the capital stock is negative, optimal investment is determined by the magnitude of the MNB from repairs. If the MNB from repairs exceeds the joint impact of the marginal value of investment and changes in the capital stock, less should be invested in new capital; the utility should focus on repairs. Under the case where the change in capital stock is positive, column three, the marginal value of investment dominates. If the magnitude of joint impact of repairs and changes in the capital stock are less than the magnitude of the marginal value of investment, the utility should increase investment. The reverse is also true. The steady state is shown as the second row of the table. It occurs when the MNB of repairs is just equal to the MNB of investment.

The qualitative comparisons of Table 2.1 may seem obvious leaving the reader to question why develop a model that predicts such a natural economic result? The answer is that the model uncovers and identifies factors that impact the utility's optimal investment decision. At a time when water utilities are faced with the predicament of failing infrastructure (ASCE, 2009), this model illustrates factors for the utility to consider which may lead to a path of optimal investment. Now we turn to empirical testing of the model's applicability using data provided by the American Water Works Association (AWWA).

2.3 Testing the Theory

Recall that given the general characterization of the utility's problem, a closed form solution to the necessary conditions is not possible. However, I established the qualitative features of the model based on the differential system of equations (2.20) and (2.21). To operationalize and test the applicability of the model I econometrically estimate the differential equation system that characterizes the utilitys investment decision. Testing the applicability of the three effect provides utilities another way to address investment in asset planning.

2.3.1 The Econometric Model

Econometric estimation of the differential system requires a conversion of the system of differential equations in continuous time to a system of difference equations in discrete time. Water systems are indexed by i and survey years are indexed by t where t is 2006 and $t-1$ is 2004. The Appendix provides the derivation that links the model and the econometric equations. Econometric Model 1 to be estimated

Table 2.2: Econometric Coefficients and Theoretical Interpretation from Theory Model

From model	Coefficient	Data Variable	Theory
$\dot{m}$	β_0	constant	$\frac{f_k + (\delta + 2\eta - \rho) f_m}{f_{mm}}$
	β_1	$\frac{c_{it}}{p_{it}}$	$-\frac{1}{f_{mm}}$
	β_2	$\frac{g_{it}}{p_{it}}$	$-\frac{(\delta + 2\eta - \rho)}{f_{mm}}$
	β_3	Δk	$-\frac{f_{mk}}{f_{mm}}$
$\dot{k}$	α_0	constant	0
	α_1	m_{it}	1
	α_2	k_{it}	$-(\delta + \eta)$

with errors ϵ_1 and ϵ_2 is:

$$\Delta m_i = \beta_0 + \beta_1 \frac{c_{it}}{p_{it}} + \beta_2 \frac{g_{it}}{p_{it}} + \beta_3 \Delta k_i + \gamma \mathbf{z}_{ij} + \epsilon_1 \tag{2.22}$$

$$\Delta k_i = \alpha_0 + \alpha_1 m_{it} + \alpha_2 k_{it} + \gamma \mathbf{z}_{ij} + \epsilon_2. \tag{2.23}$$

Table 2.2 shows the connection between the econometric coefficients and theory via the data variables. The data variables of the model, then, are the cost-price ratio with respect to repairs $\frac{c_{it}}{p_{it}}$ and to investment $\frac{g_{it}}{p_{it}}$, per capita investment m_{it}, capacity k_{it}, changes in investment Δm_i, and capacity Δk_i. The variable $\mathbf{z}$ is a vector of j specific characteristics of system i that controls for heterogeneity in terms of system size, location, water source, and financial position. Signs on the coefficients can be used to test for consistency with the theory model based on theory parameters in column four of Table 2.2. The population effect comes through α_1, α_2, and β_3, the capital effect through β_3, and the policy effect through β_2.

The theoretical model is constructed at the level of the water service-providing utility. The data is a survey of many utilities, both water and wastewater, domestic and international discussed in Section 2.3.3. The first effort to control for heterogeneity, $\mathbf{z}$, among utilities represented in the survey is to extract data for water systems in the U.S. The second effort is to control for system specific characteristics in the estimated model. Variables used to control for system specific characteristics are water source, system size, region of the U.S. where the system is located, and a ratio of total liabilities to total assets which compose $\mathbf{z}$.

The data used to construct the variable c_{it} are operating costs divided by capacity. The result is a variable in units of dollar costs per gallon capacity representing the cost of maintaining existing capacity. I convert expansion fees to the variable g_{it}. The sum of expansion fees multiplied by accounts and divided by capacity gives g_{it} whose units are dollars per gallon capacity. This variable represents the cost of expansion in per capacity terms. I calculate the average price of a gallon of water, p_{it}, as the average revenue: operating revenue divided by water sales.[4]

The stock and control variables (k_{it} and m_{it}) are by definition per capita capacity.[5] Data used to construct k_{it} are capacity divided by population. The units of k_{it} are gallons of capacity per person. I convert the five-year capital needs forecast in each survey year using a two-period moving average. Capital needs are converted to units of m_{it} (gallons of capacity per person) by dividing capital needs per person by g_{it} (dollars per gallon). The model specifies a differential system of optimal investment yet the data describes investment need. I assume that investment need given in the

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[4] The model was estimated using the average price of water and the average price (rental price) of capacity: total operating revenue divided by capacity. The model performed better using the price of water.

[5] An alternative specification of the model is in terms of dollars per person (asset value per person). The model of (2.22) and (2.23) was estimated in two specifications: in terms of dollars per person and capacity per person. Capacity per person performed better in all estimations so is the one presented here.

Table 2.3: Variables and Definitions

Variable	Obs	Mean	Std. Dev.	Definition
$\frac{c}{p}$	438	0.6675	0.1973	Ratio of maintenance cost to water price
$\frac{g}{p}$	438	3.9986	5.5829	Ratio of expansion cost to water price
k	488	329.6	212.72	Gallons of existing capacity per capita
m	377	200.73	859.91	Gallons of needed capacity per capita
region	496	1.1956	1.0051	Firm region = west then 0; south then 1; midwest then 2; northeast then 3
source	496	0.3145	0.4648	Groundwater primary source then 1, 0 othwerwise
size	496	1.7742	0.6207	Population served $<$ 3,300 then 1; $>$ 50,000 then 2; 0 otherwise
debtratio	432	0.3671	0.2295	Ratio of total debts to total assets

data proxies well for optimal investment at the utility level.

The descriptive statistics of the empirical model variables are shown in Table 2.3. Observations were lost due to some missing data. I imputed missing observations and ran the model but results were not significantly different from the model where missing observations were dropped. To avoid any error introduced by imputation I did not use any imputed data. Rows two and three in the table are ratios. Per-gallon costs to maintain existing capacity are roughly 67 percent of the per-gallon water price. Per-gallon costs to expand capacity are roughly 400 percent greater than the water price. The mean level of capital stock, k, is 330 capacity gallons per person while the mean level of capital investment needs, m, is 200 capacity gallons per person. The $\mathbf{z}$ vector variables are relatively self-explanatory. *source* describes systems water supply; roughly 30 percent of the systems rely primarily on groundwater. The system service population of utilities represented in the data ranges between 3,300 and 50,000 people hence the data reflects primarily medium to large systems that are in a relatively good equity position based on *debtratio*.[6]

2.3.2 Estimating the Model

The empirical model can be estimated under two specifications: as a difference model and as an autoregressive model. Model 1 is the difference model in equations (2.22) and (2.23). Model 2 is the following lagged model:

$$m_{it} = \beta_4 + \beta_5 \frac{c_{it}}{p_{it}} + \beta_6 \frac{g_{it}}{p_{it}} + \beta_7 k_{it} + \beta_8 k_{it-1} + \beta_9 m_{it-1} + \gamma \mathbf{z}_{ij} + \omega_1 \tag{2.24}$$

$$k_{it} = \alpha_3 + \alpha_4 m_{it} + \alpha_5 k_{it-1} + \gamma \mathbf{z}_{ij} + \omega_2. \tag{2.25}$$

I use an ordinary least squares (OLS) regression on each equation in Model 1. Testing reveals that heteroskedasticity and endogeneity are not a problem for either equation. I test for endogeneity by running an OLS regression on each equation in Model 1 followed by a two-stage least squares estimation (2SLS) regression where equations are estimated simultaneously. Hausman's specification test of 0.11, distributed as chi-squared χ^2 with seven degrees of freedom, finds there not to be a systematic difference between OLS and 2SLS estimators. A test for heteroskedasticity post estimation fails to reject the null of constant variance with a Breusch-Pagan test statistic of 0.25, χ^2 with one degree of freedom. However, Model 1 does not explain very much of the variation in the data.

Model 2 estimation results show that this is a better fit of the data than Model 1. I run an OLS regression on each equation and find that more variables are statistically significant and the R^2 shows that Model 2 explains more of the variation. Further, we run a 2SLS on the simultaneous system of equations. Hausman's specification test estimate 0.03, χ^2 with seven degrees of freedom finds endogeneity not to be a problem.

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[6] Medium to large systems defined by the EPA are those serving populations of size 3,300 to 100,000 (EPA, 2002a).

However, under the null of constant variance the Breusch-Pagan test statistic 1561.83, χ^2 with one degree of freedom, finds that the variance is not constant. To correct the non-constant variance, we re-specify Model 2 by taking the natural log of model variables. Model 3 becomes:

$$\ln m_{it} = \tilde{\beta}_4 + \tilde{\beta}_5 \ln \frac{c_{it}}{p_{it}} + \tilde{\beta}_6 \ln \frac{g_{it}}{p_{it}} + \tilde{\beta}_7 \ln k_{it} + \tilde{\beta}_8 \ln k_{it-1} + \tilde{\beta}_9 \ln m_{it-1} + \tilde{\gamma} \mathbf{z}_{ij} + \tilde{\omega}_1 \quad (2.26)$$

$$\ln k_{it} = \tilde{\alpha}_3 + \tilde{\alpha}_4 \ln m_{it} + \tilde{\alpha}_5 \ln k_{it-1} + \tilde{\gamma} \mathbf{z}_{ij} + \tilde{\omega}_2. \quad (2.27)$$

Tables 2.4 and 2.5 show the results of regressions for Model 1 and Model 3. The natural log specification of Model 3 corrects for non-constant variance by minimizing the variation. However, when I check for endogeneity by running OLS and 2SLS then comparing the estimates using Hausman's test, I find that there is a problem. I instrumentize k with the exogenous variables in the model ($\frac{c_{it}}{p_{it}}$, $\frac{g_{it}}{p_{it}}$, *source*, *size*, *region*, and *debtratio*) then run the estimation as 2SLS. The Hausman specification test 19.6, χ^2 with nine degrees of freedom, rejects the null of no systematic difference between OLS and 2SLS estimators hence 2SLS is the correctly specified model. In instrumenting the model, ln k the cost price ratio with respect to investment is a statistically significant estimator for per capita capacity while the cost price ratio with respect to maintenance is not statistically significant. The Pagan-Hall test for heteroskedasticity on 2SLS models finds that the variance is constant. The test statistic 5.4, χ^2 with nine degrees of freedom, fails to reject the null that the disturbance is homoskedastic. Thus, Model 3 is the correct specification and explains more of the variation than Model 1. The correct econometric specification is a system of simultaneous equations.

Empirical testing finds that Model 3 explains a third of the variation in the data and is a better specification. Prior to taking logs, the coefficients could provide insights to the magnitude of parameters estimated. The elasticity interpretation that comes with logs means that the signs and significance of variables remains the

Table 2.4: Econometric Results for Model 1

	m Regression			k Regression		
Variable	Coefficient	Estimate	s.e.	Coefficient	Estimate	s.e.
constant	β_0	-45.696	680.781	α_0	-6.814	40.865
$\frac{c_{it}}{p_{it}}$	β_1	925.191	575.606			
$\frac{g_{it}}{p_{it}}$	β_2	-22.060	18.575			
Δk_i	β_3	0.004	1.112			
m_{it}				α_1	-0.003	0.007
k_{it}				α_2	0.104*	0.041
region	γ_1	112.282	98.926	γ_1	6.660	8.560
source	γ_2	47.778	205.750	γ_2	41.783*	16.877
debtratio	γ_3	-955.578	500.761	γ_3	-31.497	39.606
size	γ_4	-147.926	189.744	γ_4	-17.178	13.934
R^2		0.10			0.15	
adj. R^2		0.04			0.11	
N		114			125	

$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.00$

same except that estimate are now interpreted as percentage changes rather than level changes. Table 2.6 provides six tests that determine the applicability of the model, given the data.

Consider equation (2.26), the m equation in Model 3. From Table 2.5 the significant variables are the constant, two forms of k, and the investment cost-price ratio. Using these results in conjunction with the relationship between econometric coefficients and theory predictions identified in Table 2.2 I can construct a set of qualitative tests to check for consistency between the theory and empirical models. Table 2.6 shows three consistency tests for equation (2.26).

After model specifications, the sign of β_2 in Table 2.2 is equal to the sign for $\tilde{\beta}_6$.

Table 2.5: Econometric Results for Model 3

	m Regression			k Regression		
Variable	Coefficient	Estimate	s.e.	Coefficient	Estimate	s.e.
constant	$\tilde{\beta}_4$	-4.316*	1.671	$\tilde{\alpha}_3$	1.539***	0.328
$\ln \frac{c_{it}}{p_{it}}$	$\tilde{\beta}_5$	-0.069	0.603	α_6	0.019	0.131
$\ln \frac{g_{it}}{p_{it}}$	$\tilde{\beta}_6$	-0.978***	0.135	α_7	0.164***	0.039
$\ln k_{it}$	$\tilde{\beta}_7$	4.945***	0.865			
$\ln k_{it-1}$	$\tilde{\beta}_8$	-3.589***	0.808	$\tilde{\alpha}_5$	0.619***	0.061
$\ln m_{it-1}$	$\tilde{\beta}_9$	0.168	0.109			
$\ln m_{it}$				$\tilde{\alpha}_4$	0.154***	0.034
region	γ_1	-0.144	0.135	γ_1	-0.001	0.031
source	γ_2	0.048	0.297	γ_2	0.121	0.063
debtratio	γ_3	0.488	0.715	γ_3	-0.073	0.150
size	γ_4	0.408	0.269	γ_4	-0.047	0.050
R^2		0.30			0.72	
adj. R^2		0.24			0.70	
N		108			120	

*p $<$ 0.05, **p $<$ 0.01, ***p $<$ 0.00

We know that $\tilde{\beta}_6 \neq 0$ and that the sign is determined by $(\delta + 2\eta - \rho) \gtreqless 0$. Test 1 presents this comparison with the coefficient estimate. Since $\tilde{\beta}_6 =$ -0.978 which, means that investment with respect to the investment cost-price ratio is somewhat inelastic, we know that $(\delta + 2\eta - \rho) < 0$ must be true. Assume a depreciation rate commensurate with an expected useful infrastructure life of 50 to 80 years. The mean population growth rate per year from the data is 1.75 percent. The Water Resources Development Act of 1974 requires federal water projects to use a discount rate based on the Treasury's average rate of borrowing (Kohyama, 2006). The average long-term borrowing rate paid by the treasury is 6.2 percent.[7] Our model says that the

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[7] Calculation based on the average 30 year bond rate from 1990 through 2007. For years

average utility's internal rate of discount is 5.5 percent which fits with discount rate based on the U.S. Treasury borrowing rate.

Table 2.6: Tests of Model 3 Consistency to Theory Assumptions

Equation	Test	Theory	Coefficient	Consistent with Theory	Interpretation
(2.26)	1	$\tilde{\beta}_6 \neq 0$	$\tilde{\beta}_6$ = -0.978	yes	$\delta + 2\eta < \rho^*$
	2	$\tilde{\beta}_8 < 0$	$\tilde{\beta}_8$ = -3.589	yes	$f_{mk} < 0$, $\frac{\partial m}{\partial k} < 0$
	3	$\tilde{\beta}_4 < 0$	$\tilde{\beta}_4$ = -4.316	yes	$f_m < 0$, $f_{mm} < 0$
(2.27)	4	$\tilde{\alpha}_3 = 0$	$\tilde{\alpha}_3 = 1.539$	no	missing variables
	5	$\tilde{\alpha}_4 > 0$	$\tilde{\alpha}_4 = 0.154$	yes	m impacts k
	6	$\tilde{\alpha}_5 < 1$	$\tilde{\alpha}_5 = 0.619$	yes	physical depreciation

* $\delta = [0.0125, 0.02]$, $\eta = 0.0175$, $\rho \geq 0.055$

Test 2 confirms the model assumption that the change in investment is inversely related to the change in the capital stock and elastic since $\tilde{\beta}_8$ = -3.589. This means that the marginal product of investment with respect to changes in capital is negative and is consistent with the theory. Test 3 allows us to interpret the constant term. From the empirical results recall that $\tilde{\beta}_4 < 0$ and from Test 1, that $\rho > \delta + 2\eta$. From Table 2.2 the denominator of the constant, f_{mm}, is negative which means that the numerator must be positive. By assumption $f_k > 0$ and by empirical testing $(\delta + 2\eta - \rho) < 0$ which means that $f_m < 0$. This result is consistent with the theory model, it is also the major underlying assumption of the adjustment cost model. Investment is costly to the utility in terms of foregone production since instantaneous investment does not produce instantaneous output.

Lagged investment does not play a significant role in current investment, $\tilde{\beta}_9$ is not statistically significant. This suggests that the capital stock effect plays a more

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where the 30 year bond was not available, the 20 year rate was used.

significant role in current investment than historic investment. The cost price ratio with respect to maintenance is not statistically significant. The theoretical model says that it should be included however in econometric testing, when just the cost of maintenance c_{it} is regressed rather than the ratio, c_{it} becomes significant. Model 2 finds the cost price ratio is significant with the expected sign. Correcting for heteroskedasticity with the natural log operator makes the maintenance cost-price ratio insignificant. This is due to the log operator reducing the small variation (Table 2.3) to an even smaller amount of variation.

Consider now the k equation. Test 5 shows that the impact of per capita investment is significant since $\tilde{\alpha}_4 > 0$. A one percent increase in last period investment leads to an increase of 0.15 percent in the capital stock in the current period. Further, Test 6 shows that the capital stock depreciates. For a one percent increase in the capital stock last period, 0.62 percent remains in the current period. Recall that the lhs of equation (2.23) is $k_{it} - k_{it-1}$. Model 3 has k_{it} as the lhs variable so the expected sign of k_{it-1} is positive as it moves to the rhs. The data bears out this result. While the sign is not negative, the interpretation illustrates the change in capital stock between periods. Test 4 shows that the model does not include all the variables that explain changes in the capital stock. This is likely due to aggregation issues that omit variables. Test 2 and Test 5 confirm that the optimal investment decision is dynamic and connected to the capital stock.

In terms of water system heterogeneity, system specific characteristics do not play a role in explaining investment and capital per person. The **z** vector is not statistically significant in either estimation, nor is it if variables are run as dummies instead of categorical. This makes sense under the theoretical model since heterogeneity does not enter. These system specific variables were included for completeness and their lack of significance validate that the theoretical model developed is a general, not a system specific model.

2.3.3 The Data

I construct a dataset based on the AWWA "Water and Waste Water Rate Survey" conducted in 2004 and 2006 (AWWA, 2004, 2006). The 2004 survey reports 361 respondents from the U.S. and countries abroad.[8] On average, six water or wastewater utilities per U.S. state responded. The 2006 survey reports 266 respondents from the U.S. and Canada. On average, five water or wastewater utilities per U.S. state responded to the 2004 survey. The survey collects data on rates, services provided, consumption, system characteristics, financial statements, and capital investment needs. Descriptive statistics for data used to derive our variables are given in Table 2.7. I report for U.S. water systems where data are categorized by system size, expansion fees, assets and liabilities, and capital needs.

The population and accounts data in the first category, System Size, are the sum of residential and non-residential customers. The daily water treatment production capacity survey question asks utilities for the sum of permitted production. I recognize that good engineering practices build in excess capacity, for this reason capacity proxies for the total usable capital stock in the system. Water sales record the volume sold.

Expansion fee data reflects the cost of expanding services. The impact fee covers the capital recovery cost necessary to finance trunk facilities. Trunk facilities include transmission mains, treatment facilities, and source of supply facilities. Assessment fees cover capital costs of line extensions and to extend facilities to new customers, generally residential. Connection fees, often called utility expansion charges, recover the cost of physically connecting new customers to the water system.

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[8] Countries represented in the 2004 data include: Australia, Brazil, Canada, Chile, China, Chinese Taiwan, Cyprus, Denmark, Egypt, Ethiopia, Finland, Ireland, Italy, Japan, Mexico, Netherlands, New Zealand, Norway, Philippines, Portugal, Romania, Slovenia, South Korea, Spain, Sweden, Thailand, Ukraine, and United Kingdom.

Assets and liabilities data delineates costs and revenues by type. I report costs and revenues of operating the water system. Operating costs are annual water operating expenses before depreciation. From the balance statement, total liabilities are the sum of current and long-term liabilities and long-term debt. Total assets are those of the water system. The model does not depend on utility equity so I report assets and liabilities only although the survey provides system equity data.

Table 2.7: Data Descriptive Statics with Summary Definition

	Data	Obs	Mean	Std. Dev.	Definition
System Size	accounts	496	78.47	108.67	Total accounts in thousands
	population	496	389.33	801.76	People served in thousands
	capacity	496	100.80	166.11	System capacity in million gallons
	water sales	496	18.77	42.29	Total water sales in billion gallons per year
Expansion Fees	impact	496	712.73	1354.37	Impact fee per new account
	assessment	496	349.54	1271.99	Cost to extend service to new account
	tap	496	593.56	903.47	Price per new account to connect to system
Assets & Liabilities	operating costs	496	27.91	49.01	Total operating cost costs in millions of dollars
	operating revenues	496	43.54	78.71	Total operating revenue revenue in millions of dollars
	total liabilities	496	169.19	453.11	Total debt service and liabilities in millions of dollars
	total assets	496	354.89	706.99	Total assets in millions of dollars
Capital Needs	2004	496	12.41	37.40	Forecasted capital improvement needs in millions of dollars
	2005	496	26.12	88.37	
	2006	496	22.86	65.09	
	2007	496	25.59	105.12	
	2008	496	21.65	73.26	
	2009	230	17.90	47.36	

Capital needs data gathers water systems' investment need from their capital improvement plans (CIP). The 2004 survey reported the capital needs forecast from years 2004 through 2008 while the 2006 survey reported the forecast from 2005 through 2009. By year, then, the capital needs forecast is the dollar amount that water systems will need for system expansions, upgrades, and replacements. Observations change for the 2009 forecast estimate since it occurs only in the 2006 survey. I consider the applicability of our model to U.S. water systems in the next section.

2.4 Interpreting Results

The theory of the utility's optimal investment decision explains roughly a third of the variation in the data from water utilities across the U.S. The next task is to consider how the model results may provide water utility managers with an additional instrument in their capital planning process. To do so, note that water utilities from around the country face different problems related to water infrastructure. For example, water utilities in the northern and eastern U.S. face the problem of large, old systems and a shrinking customer base which means revenues are falling. Systems in the southern and western U.S. face the challenge of meeting water demands of a rapidly growing customer base while updating aging infrastructure (Cromwell et al., 2001). These varied concerns suggest that population size and existing capital stock may influence U.S. water system investment need, a result found in our model. I will therefore discuss this further in the following section. In addition, the model illustrates how policy maker tools (water price and connection costs) may defray capital needs.

I consider the effects of population, capital stock, and policy maker tools and then interpret the results in the context of problems facing water utilities.

2.4.1 The Effects of Population, Capital Stock, and Policy

Consider Model 3 from Table 2.5. To illustrate how the population size and capital stock influence investment need and to show to what extent the policy maker may need to respond, I use the Model 3 results in per capita terms. This reduced form is:[9]

$$\ln \frac{M_{it}}{L_{it}} = 13.782 - 2.21 \ln \frac{K_{it-1}}{L_{it-1}} - 0.699 \ln \frac{g_{it}}{p_{it}}. \tag{2.28}$$

Equation (2.28) shows per capita investment need as a function of lagged per capita stock and the investment cost-price ratio. Variables are presented as ratios; however, considering the impact of variables individually allows us to apply Model 3 to infrastructure problems facing water systems. I use the elasticities produced by the log-log estimation to define the population effect, the capital stock effect, and the policy effect.

The lagged population effect suggests that for a one percent increase in population in the last period, investment need rises 2.21 percent. The capital stock effect has a lagged, inverse relationship with investment needs. This means that for an increase in the last period capital stock of one percent, current period investment need falls by 2.21 percent. The corollary is also true: if the capital stock is reduced due to infrastructure taken off line for rehabilitation and replacement need, more investment is needed and a reduction in population reduces the path of investment.

The population effect and the capital stock effect show the dynamic impact on the investment decision. The model shows, however, that the policy maker may mitigate the effects of population and deteriorating capital. The policy maker charges the customer a price g to connect to the system and a price p for dollars per gallon of water use. The purpose of g is to recover costs imposed on the system by the

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[9] I use the ln k equation from Model 3 and plug it into ln m and use only the significant variables.

new customer. The purpose of p is to recover costs of distributing water to the customer. The investment cost-price elasticity (-0.699) suggests that the policy maker can reduce the utility's investment need by increasing the connection price, g. This variable contributes to the discussion of who pays for expansion, existing ratepayers or new customers? Investment dollars from existing customers comes through p while investment dollars from new customers comes through g. A ten percent increase in g holding p constant reduces investment need by seven percent. A ten percent increase in p holding g constant actually leads to increased investment need. This suggests that the policy maker can more effectively defray the utility's investment decision by placing the expansion burden on new customers, not existing customers.

2.4.2 Implications for Water Systems

I noted earlier the multi-billon dollar investment gap that pervades the 54,000 water systems in the U.S. The average water system in the dataset (Table 2.7) forecasts annual capital investment needs at \$21 million dollars. This supports the WIN's assertion that annual infrastructure shortfalls are as much as \$23 billion dollars (WIN, 2000a). The infrastructure gift given to current water users is about to wear out leaving current and future users the responsibility of getting water infrastructure to 21^{st} century standards.

The model provides water system managers another means to address that challenge. Monitoring changes in capacity, population, and policy, and responding accordingly help the utility maintain a path of optimal investment. Water users have become accustomed to water rate policy that does not generate revenue sufficient for infrastructure replacement. The policy effect suggests that tools readily available can *de facto* defray the utility's investment need by placing the revenue burden on customers who create the need. Meeting 21^{st} century infrastructure challenges implies that the historic cost recovery method of revenue generation may need to be reevaluated. The full cost of replacement and expansion should be reflected in policy instruments.

Cromwell's Nessie Curve analysis suggests that peak replacement needs are expected in the next 30 years: ten years beyond the time frame of the multi-billion dollars needs discussed earlier (Cromwell et al., 2001). The cost analysis component of Nessie is similar to our model in that it relies on the fundamental economic decision of the MNB of replacement relative to the MNB of repairs. Both models recognize that replacing infrastructure prior to the end of its economic life is costly yet waiting until infrastructure fails may prove catastrophically costly. A "manage the crisis" approach is to wait for infrastructure to fail resulting in a management plan that perpetually has to play catch up and never gets ahead of the problem. The focus solely on capital in Nessie analysis is analogous to looking at just the capital stock effect of this model.

In tandem with Nessie, our model shows two contributions that compliment current system forecasts for replacement. The policy effect and the population effect influence changes in investment need. Well-managed water systems have CIP that are updated regularly. The data supports the fact that optimal investment is a moving target. The effects represented by our model act as guidelines towards an optimal investment decision. The model suggests that given the dynamic nature of investment, CIP should be conducted frequently paying close attention to existing capital, population trends, and prevailing policy instruments. Intricacies in the investment decision imply that the more frequent needs are assessed, the quicker the policy response can be. The customer base influences the size of investment need. In the event of an increase in the customer base, the policy maker can reduce the impact by changing the investment cost-price ratio.

2.5 Conclusions and Extensions

The data is consistent with the WIN estimate that annual under-funding estimates for water utilities are up to $23 billion dollars. The average AWWA water system forecasts capital infrastructure needs at $21 million dollars. I approach the investment gap crisis that faces U.S. water utilities using an adjustment cost model in per capita terms to explore a water utilitys capital accumulation and investment decision. The model shows that an optimal investment decision is dynamically affected by the population effect, the capital stock effect, and the policy effect. The model suggests that policy maker response may defray the population effect and the capital stock effect and thus stabilize the utility's investment decision. Empirical tests of the model find that data supports the theory thus it serves as a guideline for utilities that wish to mitigate infrastructure funding gaps and invest optimally.

I mentioned earlier that the estimated infrastructure investment gap in the U.S. is a multi-year, multi-billion dollar problem. Further, roughly 16 percent of public infrastructure investment is for water infrastructure. Turbulent economic times imply that the 16 percent slice of the federal budget for water infrastructure may grow smaller. Water infrastructure is a silent service whose economic turmoil may not be expressed during the current election cycle. Voter interest in current chaotic economic issues translates to policy maker agendas that reflect the same. Budget allocations that meet voter interests may in fact reduce public help to meet the infrastructure crisis. A lack of federal funding, a condition noted by WIN (2000a), leaves utilities to deal with infrastructure investment gaps from within. Utilities that recognize the dynamic nature of investment, adjust planning needs based on the effects we model, and employ appropriate policy instruments may mitigate their own infrastructure investment gaps and not be part of an infrastructure crisis that plagues, and is forecasted to continue plaguing, many U.S. water systems.

The general model of infrastructure investment can be made richer and offer more insights to optimal investment through a series of extensions. Capital stock and infrastructure investment were modeled generally. One extension is to disaggregate infrastructure into specific types. It may be the case, for example, that utilities have greater need in pipe rehabilitation than in treatment plant updating. Infrastructure disaggregation may capture those tradeoffs so that the investment decision could model in which types of infrastructure to invest. Historically, institutional barriers preclude water systems from charging water prices that cover more than the cost of distribution. Another extension is to identify the efficient water price in terms of infrastructure investment and the scarcity value of water.

The results suggest that the individual utility can choose investment based on population, capital, policy, and growth. Choosing investment optimally helps mitigate funding shortfalls.

Chapter 3

Estimating Impacts of Water Scarcity Pricing

3.1 Introduction

Water provision is threatened by both increased water scarcity and failing water infrastructure. Water supplies in the Western U.S. are dwindling due to the impact of a warming climate. In a recent synthesis of extant global warming studies, Saunders et al. (2008) finds that temperature increases in the West are greater than any other part of the country (with the exception of Alaska) due to more frequent and intense occurrences of drought. For example, on average the Western-coastal states have experienced a 1.7 degree Fahrenheit increase in the average temperature over the last 100 years while the mountain and southern states have seen increases of 2.4 and 2.7 degree increases respectively. Of the Western states, the change in Nevada (3.6 degrees) and Colorado (3.1 degrees) are the most drastic. These changes in weather patterns have a deleterious effect on an already arid region. Contemporaneously, unprecedented population growth in this region leads to an ever increasing urban water demand curve.[1] Water provision is also threatened by failing water infrastructure resulting from a chronic underinvestment. Management that depends on underpriced water for revenue has had to manage the infrastructure resource with sub-optimal funding; this has led to the current state of disrepair estimated at $23 billion annually to $2.2 trillion over the next 20 years (WIN, 2000a,b).

The economists' assessment of this water management problem is that prices are too low, that the true value of water is not reflected in demand-side management policy (Hanke, 1978; Martin et al., 1984; Brookshire et al., 2002). Studies that consider under-priced water include, for example, Moncur (1989) who considered implementing drought surcharges and Collinge (1994) who investigated equity coupons for promoting water conservation. Others have explicitly considered water rate structures (Griffin, 2001; Olmstead et al., 2007). Another line of inquiry is to consider non-price, demand-side management as in Renwick and Archibald (1998) and Renwick and Green (2000). Martin et al. (1984) started the scarcity value investigation when they estimated a Tucson scarcity value of 58 percent more than existing water prices (p. 57). Others have found the scarcity value to range from $1.04 to $2.39 per 1,000 gallons in Honolulu and Chicago, (Moncur and Pollock, 1988; Ipe and Bhagwat, 2002) respectivley.[2] Using a sample from California, Jenkins et al. (2003) estimate that by the year 2020 $1.6 billion will be lost in foregone value from underpriced water.

Historically, however, there are regulatory barriers that prevent a water manager from collecting the scarcity value (Young, 1986). Barriers to scarcity pricing range from cultural beliefs that water is a basic need of human life and should not be priced as a commodity at market rates (Jordan, 1999; Martin et al., 1984) to concerns for

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[1] The U.S. Census Bureau estimates that between 2000 and 2030, population growth in the Southern United States will reach 43 percent and in the West 46 percent at `www.census.gov` last accessed 18 April 2009.

[2] Original estimates ($0.58 and $1.58) converted to 2009 dollars using the Bureau of Labor Statistics inflation calculator at `www.bls.gov` last accessed 18 April 2009.

equity and the budget constraints of low income users (Griffin, 2001). Martin et al. (1984) note that many cultural belief structures hold that pricing water is similar to pricing air, that a basic life need should not be priced at all.

Concerning failing water infrastructure, Hansen (2009a) summarizes the major water infrastructure underfunding issues. The underlying condition is that existing water infrastructure is nearing the end of its economic life. Water utilities are not yet behind but face the reality that by the year 2030 expenditures on infrastructure replacement are forecasted at three and a half times greater than current expenditures (Cromwell et al., 2001). Further, the U.S. Environmental Protection Agency (EPA) estimates underfunding at $485 to $896 billion through the year 2020 but also notes that utilities can mitigate funding shortfalls with increases in capital spending at the real rate of growth (EPA, 2002b). The question thus becomes, where will utilities generate funds to increase capital spending? This paper offers a potential solution through optimal water pricing.

The purpose of this paper is twofold. First I evaluate the extent to which management of urban, groundwater pumping promotes sustainable use of the aquifer thus preventing premature exhaustion of the resource. Optimal control of pumping suggests an efficient price path that includes the water scarcity value, which is the equivalent to marginal user cost. I find that for the case study of Albuquerque, New Mexico a growing metropolis in the desert Southwest, current water prices are approximately 20 percent of the price level that signals scarcity. A second contribution of this paper deals with scarcity pricing as an infrastructure investment mechanism. Utilities need increased revenue for water infrastructure investment. I dynamically simulate the extent to which collecting the water scarcity value can defray utility investment shortfalls by considering simulated profits. The results suggest that the policy maker may get “two birds with one stone” in a single policy prescription. Efficient water allocation and revenue generation for investment projects may simultaneously be accomplished by water pricing that reflects the marginal user cost.

I develop the model of optimal groundwater pumping in Section 3.2 and with dynamic simulation evaluate the "two-for-one" hypothesis in Section 3.3. The simulation results have implications for existing urban water policy discussed in Section 3.4. Conclusions and extensions are in Section 3.5.

3.2 Theory

Consider the water manager whose task is to manage the groundwater resource that supplies water to a community. Let the stock of available water (state variable) be measured by the height of the water table $h(t)$ above a reference point, feet above sea-leavel in this framework. The manager draws from the aquifer $w(t)$ (control variable) water units per time period t (acre-feet per year) to meet the water needs of the population $n(t)$.

3.2.1 Social Welfare

The social welfare function is the difference between social benefits and costs, or net benefits. The social benefit to the population depends on the manager's water management strategy for groundwater pumping represented by $w(t)$ and the size of the population $n(t)$. Social benefits are $B\left[w(t), n(t)\right]$, $\forall\ t = 1, ..., T$. I model social benefits using the inverse form of urban water demand as the integrand in:

$$B\left[w(t), n(t)\right] = \int_0^{w(t)} p\left[z, n(t)\right] dz. \tag{3.1}$$

where z is the variable of integration. Assume that $B_w > 0$ and $B_{ww} < 0$: as the manager provides more water to the population, benefits increase but at a decreasing rate. Following Capello and Camagni (2000), assume that $B_n > 0$ and $B_{nn} <$

0. Capello and Camagni challenge the optimal city size hypothesis of the 1960s and 1970s. They suggest optimal city size is a function of many factors, including population where they estimate economies of scale from the population size. However, they do find dis-economies which they call urban overload. Thus, assume diminishing marginal benefits from increased population.

I model the water manager's total cost function as:

$$C\left[w(t), h(t), n(t)\right]. \tag{3.2}$$

Consistent with economic theory, $C_w > 0$ and $C_{ww} > 0$. Following previous work on groundwater modeling, assume $C_h < 0$ (Gisser and Sanchez, 1980; Sloggett and Mapp, 1984; Brill and Burness, 1994; Knapp et al., 2003) and $C_{hw} < 0$. The total cost to the water manager is inversely related to aquifer height; as water table drawdown increases the manager must use more energy to retrieve water supplies. A higher water table means lower energy needs. Drawing on Griffin's cost function specification, population is modeled as part of the manager's total cost function since an increase in population requires the manager to use more resources with which to deliver water thus $C_n > 0$ (Griffin, 2001). This may include the cost of connecting the next new customer to the existing water system (e.g., utility expansion costs) or an increased need for staff and administration.

3.2.2 Groundwater Constraint

The manager's task is to pump $w(t)$ from a groundwater aquifer to maximize net benefits. I model available groundwater by the height of the water table, $h(t)$, to indicate supply. The initial supply is thus measured by $h(0) = h_0$ feet above sea level and the supply is exhausted when aquifer height reaches a minimum at h_{min}. The change in aquifer height is described by the transition equation,

$$\dot{h}(t) = f[w(t); \Theta], \tag{3.3}$$

where height of the water table changes with pumping, $w(t)$, and Θ, a vector of hydrologic parameters that impact available water. Assume $f_w < 0$ and that the pumping impact on aquifer height is linear, thus $f_{ww} = 0$. Further, $f_{\Theta} \gtrless 0$, which means that the impact of the hydrologic parameters varies by parameter.

3.2.3 Constrained Welfare Maximization

Assuming the water manager is interested in sustainable water management, and given an initial height of the aquifer $h(0) = h_0$, the manager's problem is to choose optimal water pumping $w(t)$ over a fixed time horizon, $t \in [0, T]$, where the terminal time is fixed. The manager's problem is:

$$\max_{w(t)} \quad V = \int_0^T e^{-\rho t} \left[B\left(w(t), n(t)\right) - C\left(w(t), h(t), n(t)\right)\right] dt \tag{3.4}$$

subject to:

$$\dot{h}(t) = f(w(t); \Theta)$$

$$h(0) = h_0, \quad h_{min} \leq h(t) \leq h_{max}, \quad h(T) \text{ and } T \text{ fixed}$$

where ρ is the social discount rate.

The present value Hamiltonian to solve the manager's problem is given by:

$$H = e^{-\rho t} \left[B\left(w(t), n(t)\right) - C\left(w(t), h(t), n(t)\right)\right] + \lambda(t) \left[f\left(w(t); \Theta\right)\right], \tag{3.5}$$

where $\lambda(t) = \mu(t) e^{-\rho t}$. The conditions necessary for an interior solution include:[3]

$$\frac{\partial H}{\partial w} = 0 \Leftrightarrow e^{-\rho t}(B_w - C_w) + \lambda f_w = 0 \tag{3.6}$$

$$-\frac{\partial H}{\partial h} = \dot{\lambda} \Leftrightarrow \dot{\lambda} = e^{-\rho t} C_h \tag{3.7}$$

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[3] Time arguments dropped for ease of mathematical presentation.

$$\frac{\partial H}{\partial \lambda} = \dot{h} \Leftrightarrow \dot{h} = \left[f(w(t);\Theta)\right], \tag{3.8}$$

where (3.6) is the dynamic optimization condition and

$$\lim_{t\to T} e^{-\rho t} H\left[w, h, n, \lambda; \vec{\beta}\right] = 0 \tag{3.9}$$

is the transversality condition where $\vec{\beta}$ is the vector of parameters in the optimization.

The manager's optimal path of groundwater pumping is found by taking the time derivative of (3.6), substituting in the necessary conditions, and solving for $\dot{w}$.[4]

$$\dot{w} = \left(\frac{1}{B_{ww} - C_{ww}}\right)\left[\rho(B_w - C_w) - \dot{n}(B_{wn} - C_{wn}) + \dot{h}C_{wh} - \dot{\lambda}e^{\rho t} f_w\right] \tag{3.10}$$

The sign of $\dot{w}$ is determined by marginal net benefits and the rate of change therein, the effects of population, stock, and opportunity cost.

3.2.4 Interpretation

Consider the interpretation of the necessary conditions. From equation (3.6),

$$\lambda = -\frac{\left[e^{-\rho t}(B_w - C_w)\right]}{f_w} > 0, \tag{3.11}$$

such that λ is the marginal increase in the value of the manager's objective given an increase in aquifer height. Further, $(B_w - C_w) \geq 0$ and $f_w < 0$ imply $\lambda > 0$.

From equation (3.6) we see an important policy consideration for the water manager. With rearrangement,

$$P = MC + MUC \tag{3.12}$$

where $P = B_w$, $MC = C_w$, and $MUC = -e^{\rho t}\lambda f_w$. Note that B_w is the marginal benefit of the next water unit, that is it is the per unit price of water. C_w is the

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[4] Dot notation indicates the derivative of a variable with respect to time, i.e. $\frac{\partial w}{\partial t} = \dot{w}$.

marginal cost of pumping and λ is the marginal value of a foot of aquifer height. As aquifer height decreases, λ is the opportunity cost of not having that foot of aquifer height available for future use. Thus, MUC is the marginal user cost in current value. The important policy consideration is price equals marginal cost plus marginal user cost. This means that prices that are set to recover only MC are inefficiently low; customers will consume more water than is efficient if MUC is not part of the price.

Adjoint equation (3.7) suggests that the sign on $\dot{\lambda}$ depends on whether aquifer height is increasing or decreasing since $C_h < 0$. Once a foot of the aquifer height is gone, production costs in all future periods increase. This means that the marginal user cost reflects forgone marginal net benefits of all future periods. Thus, from equation (3.12), MC increases since the aquifer height falls and marginal net benefits in subsequent periods are less. A foot of aquifer height near the surface is more valuable to society than at greater depths because deep water is more costly to produce.

Consider now the optimal pumping program, equation (3.10). The denominator of the first term in parentheses, $\frac{1}{B_{ww} - C_{ww}}$, is the rate at which marginal net benefits change, which by assumption is negative. Marginal net benefits, $\rho(B_w - C_w)$, are by assumption non-negative and are here weighted by the discount rate.

The population effect impacts pumping through $\dot{n}(B_{wn} - C_{wn})$. This is the marginal net benefit of water with respect to changes in the population, which means that it constitutes the social net benefit of more people using water and impacts optimal pumping. Since the change in population could be positive or negative, the sign of the population effect is ambiguous.

The resource itself impacts the optimal pumping path through $\dot{h}C_{wh}$. Aquifer height impacts pumping through the impact on the cost function. The marginal change in costs from aquifer changes, multiplied by the change in aquifer height impacts the optimal pumping decision. This means that the sign of the stock effect is ambiguous and varies with changes and direction of changes in aquifer height.

The opportunity cost of foregone aquifer height impacts optimal pumping through the term $\dot{\lambda} e^{\rho t} f_w$. Recall that marginal user cost captures the fact that a foot of aquifer height used today cannot be used tomorrow. From equation (3.7), recall that the change in opportunity cost is negative and since $f_w < 0$, the sign of the opportunity cost impact is positive.

Given the interpretation of the arguments of $\dot{w}$, there are many possible combinations for which $\dot{w}$ is positive, negative, or zero. For example, increasing aquifer height and decreasing population suggest a different optimal pumping case than decreasing aquifer height and increasing population. However, as long as more water is pumped than recharged, aquifer height decreases. Further, many water utilities experience growth in the customer base, thus $\dot{n} > 0$. This is especially true in the Southern and Western U.S. where 30-year forecasted population growth rates reach 43 and 46 percent respectively.[5]

In an effort to understand optimal water pumping in practice, I simulate the model for conditions in Albuquerque, New Mexico where $\dot{h} < 0$ and $\dot{n} > 0$. Under these two conditions, the change in optimal pumping is dependent on the magnitude of marginal net benefits relative to the the sum of magnitudes of the other arguments of $\dot{w}$. Thus with simulation I determine the sign of $\dot{w}$. The manager's maximization problem is solved by the system of differential equations given in (3.3), (3.7), and (3.10). Recall that equation (3.12) suggests what optimal water pricing, in dollar per acre foot, should be on the path of optimal groundwater pumping. These equations become the foundation for the simulation model in the next section.

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[5] See note 1.

3.3 Dynamic Simulations

The purpose of the groundwater model of the previous section is to create a framework to evaluate the extent to which a single policy prescription, controlled groundwater pumping, can mitigate the water manager's two-fold predicament (scarce water resources and failing infrastructure). With the framework in place, I now use dynamic simulation to evaluate the impacts of controlled groundwater pumping.

In order to simulate the model, the general framework requires specific functional forms discussed here. Recall that the model in the previous section is in general form and continuous time. The simulation model is in numerical form and discrete time. I refer to the general model with general notation and specific notation, model variables spelled out, for discussing the simulation model. I apply the general model to a specific case study of Albuquerque, New Mexico such that results are germane to this simulation and study area. Data, discussed next, is used to econometrically estimate water demand and utility costs. Finally, this section provides the initial values and parameters used in the simulation.

3.3.1 Data

The Albuquerque Bernalillo County Water Utility Authority (ABCWUA), the principal water services provider to the Albuquerque metropolitan area, provided total revenue and billed water unit data from January 1994 through December 2004 which constitutes 132 observations. Total revenue is the sum of charges for water units, sewerage units, conservation surcharge fees, and wasted water fees. Billed water units are measured in cubic-feet.[6] The utility provides water to residential, commercial, industrial, and institutional customer service types. This means that the data are at

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[6] 1 unit $= 100$ ft^3 $= 748$ gallons

the utility-wide level and reflect behavior of all customer types. Thus, the estimated water price and monthly production reflect the use of all customer types.

Aquifer height data is retrieved from the United States Geological Survey (USGS) data archive website for a monitoring well located near the center of Albuquerque (USGS).[7] From the land surface elevation of 4,980 feet above sea level, depth to water is measured periodically from year 1957 through 2008. In the period of the ABCWUA data, January 1994 through December 2004, some aquifer height observations are missing. I impute the missing observations following the method of multiplicative decomposition where recorded data from before and after the missing data are used to estimate missing observations controlling for time trends and seasonal factors (Bowerman and O'Connell, 1993, p. 324).

Table 3.1: Data Summary Statistics

Data	Definition	Units	Mean	Std. Dev.
price	Average revenue per unit	$ per acre foot	2,546	1,672
water	Billed monthly water	acre feet	4,250	3,362
cost	Monthly operating cost	$ in thousands	8,580	4,326
account	Accounts receiving service	accounts	128,746	42,233
height	Water table height in feet above sea level	feet	4,919.8	3.37

Table 3.1 shows the descriptive summary statistics for the data. Following the convention in the literature, I estimate average water price by dividing monthly total revenue by monthly billed water units and then convert it to acre-feet[8] for the simulation model. ABCWUA did not provide monthly operating cost data. These are imputed by taking the ratio of yearly total revenue to total operating cost reported on the utility's annual financial statements (ABCWUA, 2005) and apply that ratio to the monthly total revenue to produce an estimated monthly total cost.

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[7] This model does not account Rio Grande surface water diversion in Albuquerque.

[8] 1 acre-foot = 325,851 gallons

With these data I estimate benefits and costs, or social welfare in the next section.

3.3.2 Benefits and Costs

To simulate the general model requires a functional form for the benefit function [equation (3.1)] the cost function [equation (3.2)] and the social welfare function [equation (3.4)]. I econometrically estimate a water demand equation and a long-run total cost equation to recover the partial derivatives and functional forms that are needed to simulate the model.[9] Demand and cost are estimated using the data described in Table 3.1.

Since it is for use in the simulation model where the model does not implicitly control for seasonal water use, I use ordinary least squares (OLS) regression to estimate a linear demand function.

$$\begin{aligned} water_t = \;& 1294 - \; 0.97\, price_t + \; 0.04\, account_t \\ & (719) \qquad (0.12) \qquad\qquad (0.005) \\ & (s.e.) \quad N = 132 \quad \bar{R}^2 = 0.57 \end{aligned} \tag{3.13}$$

Equation (3.13), in water units acre-feet, is an estimated water demand function at the utility-wide level for ABCWUA, which reflects behavior of all account types. Standard errors are in parentheses. Estimates are significant at the 95 percent level of confidence. The Breusch-Pagan test for heteroskedasticity fails to reject the null which is constant variance. The estimated parameter on *price* indicates that for a one dollar increase in the average price, monthly quantity demanded falls by 0.97 acre-feet (316,000 gallons) per month. The price elasticity of demand, evaluated at the mean *price* and *water* is -0.58. This suggests that for a ten percent increase in average water prices utility-wide, water quantity demanded would decrease by 5.8 percent which means this estimated demand is price-inelastic. Brookshire et al.

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[9] Econometric estimations were done in Stata version 10©.

(2002) summarize previous water demand studies, of which -0.58 closely fits and is similar to -0.62 estimated in Gibbs (1978) and -0.61 in Hansen (2009b) where both studies use average price. The elasticity estimate here is very similar to the mean in the meta-analysis in Espey et al. (1997) which is -0.51.

Using the estimated parameters of equation (3.13), I populate the social welfare function [equation (3.1)] with the water demand partial derivatives so that benefits become:

$$benefit_t = 1324.31\, water_t - 0.002\, water_t^2 + 0.04\, account_t \times water_t. \tag{3.14}$$

Estimated parameters are consistent with theory since, from Section 3.2, $B_w > 0$, $B_{ww} < 0$, and $B_n > 0$.

The long-run cost equation that I estimate is:

$$\begin{aligned} cost_t = {} & \underset{(54.52)}{367.58\, water_t} - \underset{(0.01)}{0.07\, water_t \times height_t} - \underset{(6.1 \times 10^{-5})}{2.1 \times 10^{-4}\, water_t^2} \\ & + \underset{(3.23 \times 10^{-8})}{1.06 \times 10^{-8}\, water_t^3} + \underset{(0.004)}{0.032\, account_t}. \\ & (s.e.) \quad N = 132 \quad \bar{R}^2 = 0.98 \end{aligned} \tag{3.15}$$

Equation (3.15), in thousands of dollars, is an estimated cost function without a constant term, which makes the interpretation long-run. Standard errors are in parenthesis and the variance is non-constant according to White's test for homoskedasticity, which is 34.8. I estimated standard errors using the robust method in STATA so although the model may suffer from non-constant variance, it is for use in a simulation which means the error across simulation scenarios is constant. The estimated cost equation is consistent with the theory discussed above. Marginal cost, C_w, is positive but decreases with aquifer height. This implies that water drawn from greater depths is more costly than water near the surface. Further, $C_{ww} > 0$ for $water \geq$ 4,375 acre-feet which verifies that marginal cost increases with monthly production.

3.3.3 Hydrology and Population

The theoretical model includes equations for the stock of available water [equation (3.3)] measured by water table height and a differential equation for population, $\dot{n}$, in the optimal pumping program [equation (3.10)]. I did not econometrically estimate these; instead I rely on the literature and calibrated parameters to populate the equations.

Based on the seminal work in groundwater management by Gisser and Sanchez (1980), the functional form of the aquifer height transition [equation (3.3)] is modeled as:

$$h_{t+1} - h_t = \frac{r + (\alpha - 1)\, water_t}{A s^y}, \tag{3.16}$$

where r is the annual natural water recharge (acre-feet per year) into the water table and α is the return flow coefficient (unitless) that measures the fraction of $water_t$ that returns to the resource where $0 \leq \alpha \leq 1$. Reservoir parameters that affect the total aquifer volume are A, the acreage overlying the groundwater aquifer assumed equal to the geographic size of the Albuquerque service area and s^y, the specific yield coefficient (unitless) that measures the porous space where water exists in the water table.

I model population growth following the Verhulst logistic equation (Clark, 1990, p. 11) which, applied to our framework, is:

$$n_{t+1} - n_t = \eta\, n_t \left(1 - \frac{n_t}{K}\right), \tag{3.17}$$

where η is the population growth rate and K is the carrying capacity. This is used in the optimal pumping program to identify the number of customer accounts at time t where I assume three people per account.

3.3.4 Simulation Initialize

Initial values and parameters are set based on empirical data, model calibration, and estimated initial values. Initial values and parameters used to begin the simulation are given in Table 3.2.

I estimated η, the population growth rate, and K, the carrying capacity, by calibrating the model so that simulating equation (3.17) individually replicated Albuquerque population data from the Bureau of Business and Economic Research at the University of New Mexico (BBER, 2009) for years 1994 to 2004. An annual population growth rate of 1.2 percent and a carrying capacity of 2 million best replicated the population data. The annual population growth rate used to project growth by the ABCWUA over the same period is 1.1 (ABCWUA, 2005). For λ_0, I estimate the initial value based on parameters called for by equations (3.7) and (3.11). The estimate of \$185 million means that a foot of aquifer height that is lost today imposes a cost on all future users in the form of foregone future marginal net benefits.

Inflation, through its impact on price, determines water production and aquifer height under status quo management. Historically average annual inflation has been three percent and will be applied here.[10] The choice of appropriate social discount rate can quickly become an ethical judgement based on how the manager views future generations relative to current generations. However, the Water Resources Development Act of 1974 states that in federal benefit-cost analysis, the chosen discount rate should closely mirror the long term U.S. Treasury rate of borrowing (Kohyama, 2006). I ascertain that four percent reflects the Treasury 20-year borrowing rate and is the best choice for discounting net social benefits.

Annual recharge requires a slightly less objective approach. Scientific estimates of recharge vary widely depending on the estimation method and hydrologic assump-

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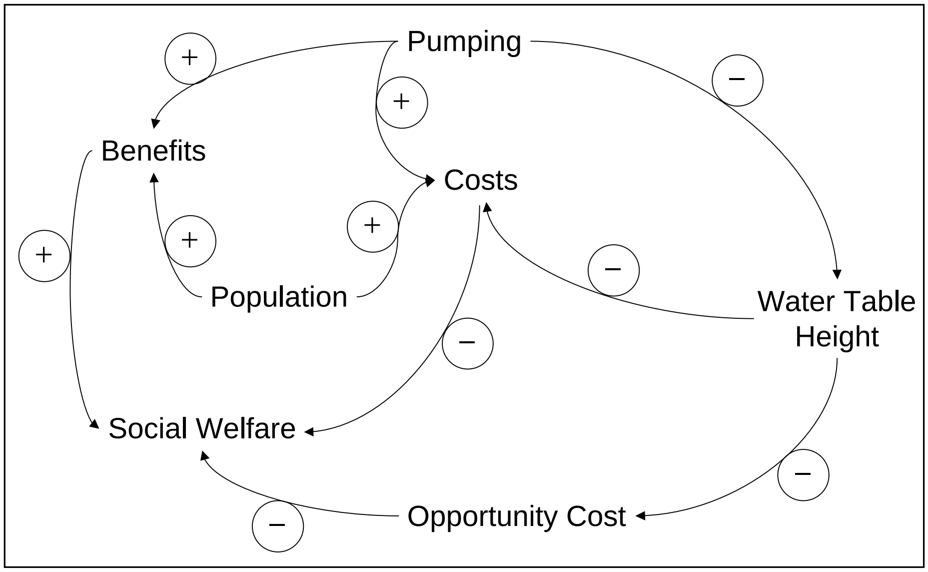
[10] Retrieved at `www.bls.gov` last accessed 18 April 2009.

tions, many of which may change within the given geographic region. McAda and Barroll (2002) and Archambault (2009) use 30 thousand acre-feet annually yet Kuss (2005) suggests that recharge can vary from 11 thousand acre-feet to 72 thousand depending on snow pack levels. The estimate I use falls within the Kuss estimated range although there may actually be much variation in annual recharge. The fact that the aquifer height data shows a decrease suggests that pumping has been greater than recharge.

Figure 3.1: Causal Loop Diagram of Simulation Model



I ran the simulations with Powersim Studio 7© over a 40-year time horizon with the simulated month beginning January 2005 on a monthly time step. Figure 3.1 shows the causal loop diagram that depicts the simulation model. Circled positive and negative signs indicate the impact from one variable to the next and are in accordance with the theoretical model results.

Table 3.2: Simulation Symbols, Definitions, and Values

Symbol	Definition	Unit	Value
w_0	Initial monthly pumping[a]	acre-feet/month	5,310
p_0	Initial per-unit water price[b]	dollars/acre-foot	1,564
h_0	Initial aquifer height[c]	feet above sea level	4915.47
λ_0	Initial scarcity value	$/foot of aquifer height	185,059,395
n_0	Initial study area population[d]	people	486,676
$account_0$	Initial number of accounts served[e]	accounts	161,055
A	Total study area[f]	acres	128,000
s^y	Aquifer storativity coefficient[g]	unitless	0.2
r	Annual estimated recharge[h]	acre-feet/year	54,000
α	Return flow coefficient[i]	unitless	0.059
η	Annual population growth rate[j]	%/year	1.2
K	Carrying capacity of study area[j]	people	2,000,000
ρ	Annual rate of discount[k]	%/year	4
δ	Annual inflation rate[l]	%/year	3
T	Simulation years	years	40

[a] From ABCWUA data, December 2004 adjusted for ten percent system loss.

[b] From ABCWUA data, December 2004 average revenue per acre-foot.

[c] Aquifer height at USGS site #350824106375301 on 1 September 2004 (USGS).

[d] Albuquerque population 2004 (BBER, 2009).

[e] From ABCWUA data, December 2004 total accounts.

[f] Earp et al. (2006) reported in Albuquerque's Environmental Story.

[g] McAda and Barroll (2002) use 0.2 in their Middle Rio Grande (MRG) simulation.

[h] Estimates vary depending on calibration method. We use the average MRG recharge from Kuss (2005).

[i] MRGWA (1999) reports this as a seepage parameter for the MRG.

[j] I assume these based on calibrating equation (3.17) with Albuquerque data.

[k] Based on Water Resources Development Act – 1974 and U.S. Treasury long-term rate (Kohyama, 2006).

[l] Average annual inflation from 1994 to 2004 at bls.gov last accessed 18 April 2009.

3.4 Results

I compare two scenarios: the optimal pumping program and a pumping program associated with a pre-determined price path, where prices increase at the rate of inflation. Sensitivity analyses include varying rates of population growth. Optimal water pumping suggests an optimal water price path that I illustrate. Finally, I consider impacts to social welfare, the water utility, and customer behavior in the presence of optimal water pumping and pricing.

3.4.1 Status Quo versus Optimal Control

Status-quo water-pumping management (SQM) represents the case where an urban water manager pumps water to meet the demand of consumers without considering resource costs. For the manager to cover operating costs and plan for future investments, a manager in a well-managed water utility charges prices that cover costs and capital projects. Without considering the impact to costs from an aquifer height reduction, the manager may believe that costs increase due to inflationary pressure. This means that revenue expectations, and prices, should rise at the rate of inflation.[11] I consider SQM a second-best alternative to optimally controlled water pumping (OCM). For SQM, the simulation model uses the initial water price listed in Table 3.2 and increases water prices at the rate of inflation, δ. Water use is determined by the demand function in equation (3.13).

Equation (3.10) constitutes the optimal water pumping program. This is the program that maximizes net social benefits subject to the groundwater resource constraint. The first part of the manager's predicament is increased water scarcity

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[11] Contra Costa Water Utility District in the California Bay Area follows a rigid practice of water rate increases based on the rate of inflation to meet operating and future capital expenditures (Niehus et al., 2008).

due to diminished groundwater availability and population growth. Thus, I consider how the aquifer is affected by OCM vis-a-vis SQM. Figure 3.2 shows the simulated results of the aquifer height which compares OCM to the SQM.

Figure 3.2: Water Table Height Comparison from Optimal Management to Status Quo Management

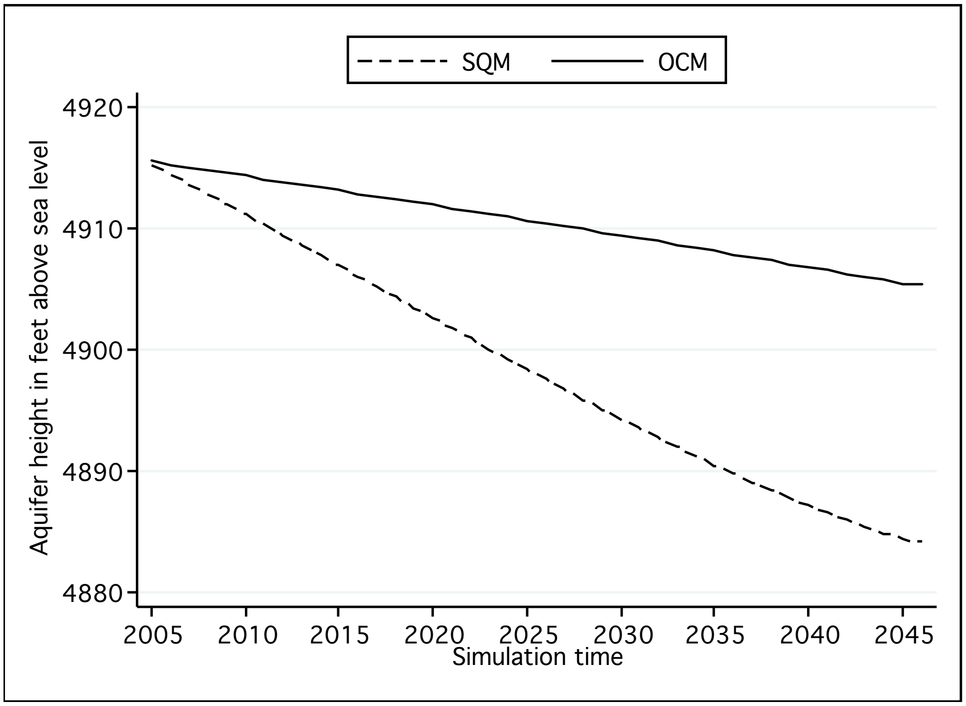

Figure 3.2 shows that the status-quo aquifer height reaches 4,884 feet above sea level by 2045. Given the starting value, this is a 40-year aquifer height reduction of 31 feet. Aquifer height data from 40 years in the past indicates that for the USGS monitoring well used here, the change in aquifer height is 45 feet.[12] This suggests that SQM has an impact on customer behavior and can reduce the amount to which the aquifer height declines illustrating the SQM as a second-best alternative. SQM reduces aquifer height less than actual management. The figure also shows the

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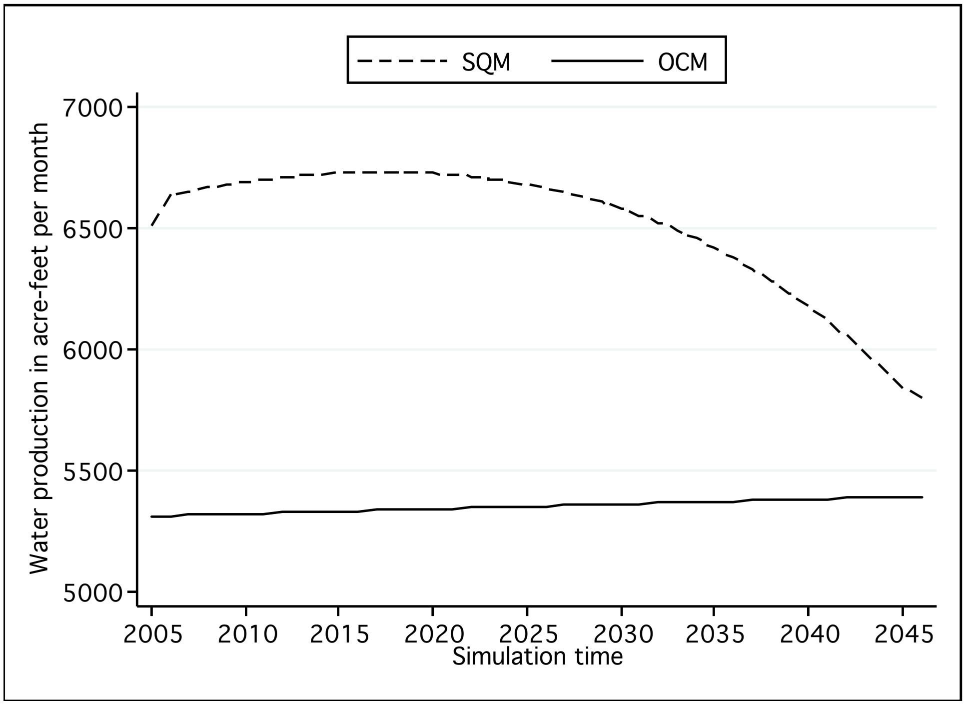
[12] Water table height in some parts of Albuquerque have dropped as much as 160 feet over the same time interval.

results of the OCM; the water level decline is not as much as SQM. By 2045, the aquifer height under the OCM is 4,906 which is a 40-year reduction of 9.8 feet. OCM preserves 21.6 feet of aquifer height over SQM. For the manager, this means that the largest extent to which groundwater scarcity can be mitigated is by following OCM. The simulated recharge rate is still less than monthly water production which means there will be aquifer mining. However, OCM reduces aquifer height 68 percent less than the next best management alternative while meeting the water needs of 690,000 people (population in 2045).

The impact on customer behavior is seen through changes in the monthly water production. Figure 3.3 shows differences in monthly production from OCM and SQM. Through simulated year 2020, monthly water production remains relatively unchanged with SQM. Then, there is a precipitous reduction in monthly production from year 2020 to 2045. This is due to inflation adjusted water price movement along the demand curve from the price inelastic region to the price elastic region. At sufficiently high water prices consumers reduce their use.

The figure also shows that monthly production steadily increases with OCM but at a small rate of change. The large fluctuation seen with SQM is not observed with OCM, which means the growing population makes do with less. In the simulation, equation (3.10) is positive throughout which means that the population effect dominates the effect of the resource and opportunity cost. That is, the social benefit function is increasing because new people in the system are using water, which means that it is optimal for the manager to increase pumping. Notice, however, that the increase is very small. This means that average water use per person decreases; at simulation time 2005 average water use is 118 gallons per person per day (GPCD), at time 2045 under OCM average use is 85 GPCD which is 5,389 acre feet per month. With SQM, monthly production in 2045 is 5,911 acre feet per month which is 93 GPCD.

Figure 3.3: Water Production Comparison from Optimal Management to Status Quo Management



3.4.2 Sensitivity Analysis

The simulation model is sensitive to at least four parameters, δ, ρ, r, and η of which I report sensitivity to the population growth rate. Consider how OCM is impacted from three levels of the population growth rate since it is the parameter that policy may influence in how urban development is approached. The base case represents population growth equal to 1.2 percent from Table 3.2. The "slow" case represents population growth equal to 0.5 percent and the "fast" case represents growth at 3 percent. Some regions of the U.S. may experience zero or negative population growth, e.g. the large northern U.S. cities (Cromwell et al., 2001), while other regions may experience rates much higher than the one we use, e.g. Nevada or Arizona.[13] However, the three cases I consider constitute possible optimal water pumping outcomes on a spectrum of population growth rates. Figures 3.4 and 3.5 show how with OCM, population growth affects the results.

Figure 3.4: Water Table Height for Three Population Growth Rates

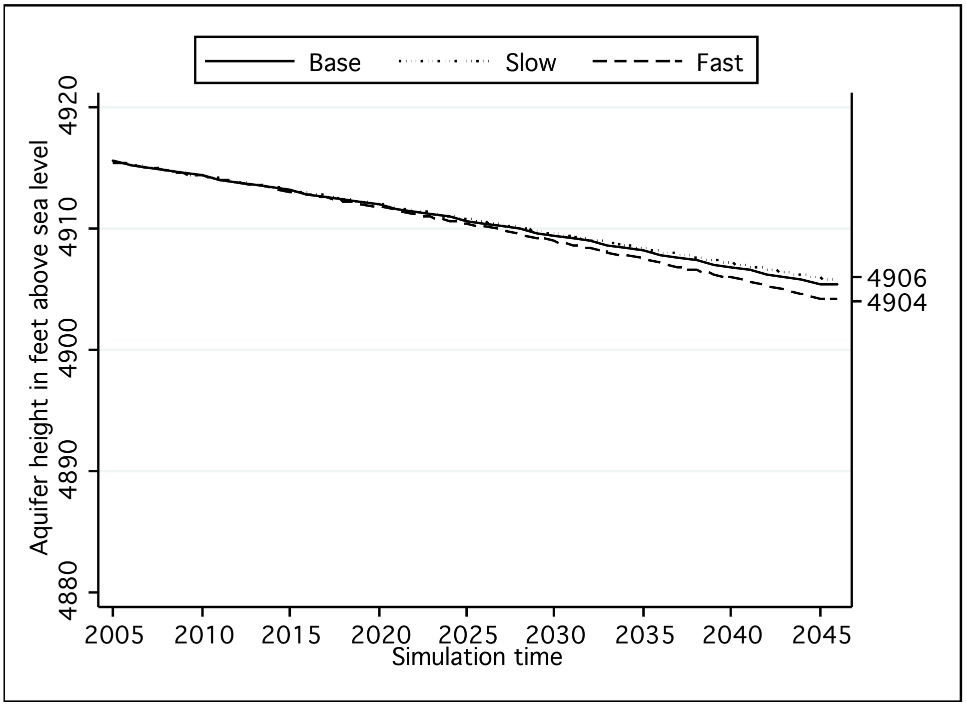


Figure 3.4 shows the water table height, optimally managed, for three cases of population growth. The terminal height for the base case, slow, and fast is 4906, 4906, and 4905 respectively. Consider these differences from the perspective of gallons of water. Recall that the total area of the study is 128,000 acres and that the specific yield is 0.2 (see Table 3.2). This means that in a one-foot slice of the aquifer, there are 25,600 acre-feet of water. The differences in water table height thus translate to 12,442 acre-feet of water between the base and slow growth and 29,133 acre-feet for the difference between the base and fast growth. This result implies that an optimally managed water pumping program responds to changes in population

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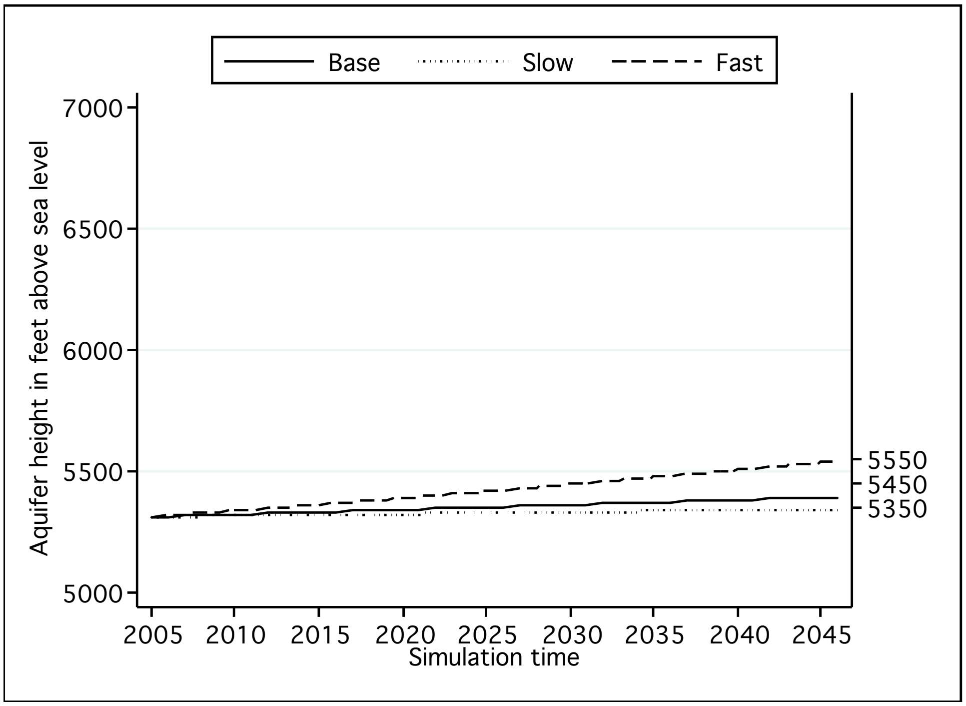
[13] See note 1.

Figure 3.5: Optimal Production Path for Three Population Growth Rates



growth. Further, although not shown in the figure, water table height under the fast case and SQM is 4,842 feet; this suggests that OCM preserves 64 feet of aquifer height over the alternative.

The optimal production path is shown in Figure 3.5 for the three population growth cases. At year 2045, base case monthly water pumping is 5,389 acre feet, for the slow growth case it is 5,341, and for the fast growth case is 5,528. Analogous to the impact on water table height, the optimal pumping program adjusts for increasing population.

I use an elasticity measurement of the impact of the population growth rate on water production on the optimal path that is:

$$\epsilon = \frac{\%\Delta \text{Water Production}}{\%\Delta \text{Population Growth Rate}},$$

to identify the relationship between OCM pumping and population growth. The average elasticity for the difference in the base to slow case and the base to fast case is 1.4.[14] This suggests that on the optimal path, for a one percent increase in population, monthly production increases by 1.4 percent. This implies that for a water manager managing urban growth, population growth and increased monthly water use is not a one-to-one mapping, water use will have to increase at a rate in excess of the population growth rate.

3.4.3 Scarcity Pricing

In the theory and simulation model, monthly production is the control variable. That is, the manager pumps the optimal amount from the aquifer to maximize net social benefits, equation (3.4). Recall from the rearrangement of the optimality conditions, equation (3.12) is the function that describes the marginal benefit of the next unit of consumption to society. It is the true value of the next consumption unit to society since it incorporates the cost of pumping water and the cost of not having water units available for future use. The manager could charge this optimal, full-cost price per unit and get the same monthly production amount as controlling monthly production. In fact, the manager should charge a price similar to equation (3.12) where price equals marginal cost plus marginal user cost to optimally use the resource.

Figure 3.6 shows the price path for the two management possibilities, SQM and OCM, with the two marginal costs that sum to the OCM price path, MC and MUC. The MUC is the lightly shaded, vertical distance from MC to the the OCM price. In year 2005, the optimal price is \$7,782 per acre-foot and in year 2045 it is is \$18,533 per acre-foot. This implies that the MUC in the first period is \$6,802 per acre-foot

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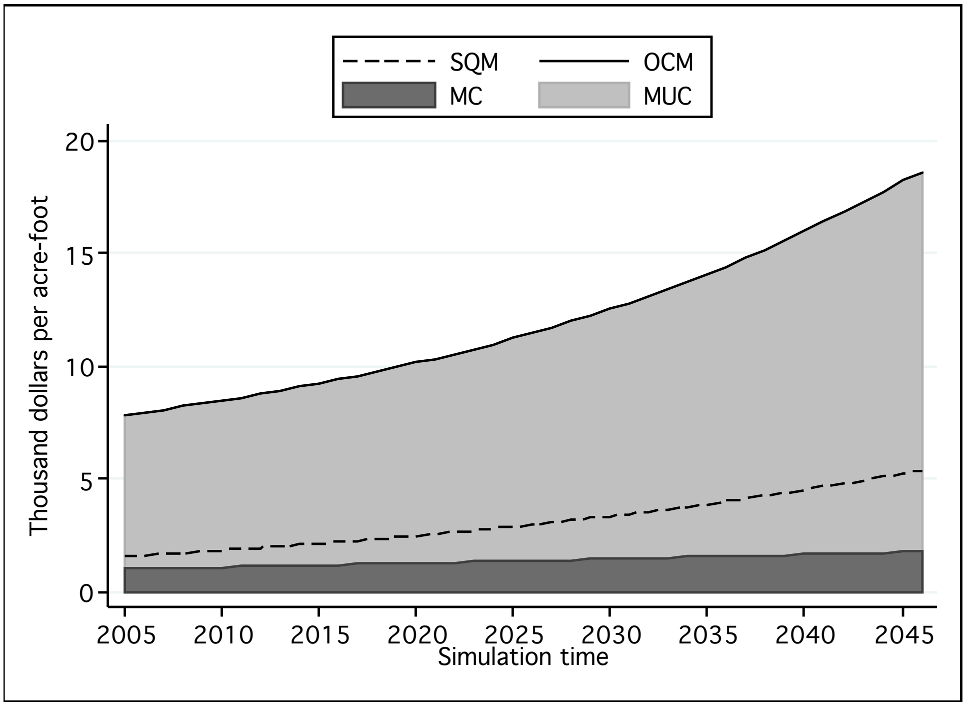
[14] For the base to slow $\epsilon = \frac{0.9}{0.7}$ and for the base to fast $\epsilon = \frac{2.55}{1.8}$.

and in the last period is $16,773 per acre-foot. In current value terms, there is a steady increase in the MUC which implies that prices under OMC steadily increase.

Figure 3.6: Two Price Paths, SQM and OCM, with Marginal Pumping Cost MC and Marginal User Cost MUC



The MUC suggests that for this case study in year 2005, prices with SQM are approximately 20 percent of the the price level with OCM; by year 2045 SQM prices are 28 percent of OCM prices. Figure 3.6 shows that although SQM is a second-best alternative, some MUC is captured; there is some MUC (gray area) below SQM prices (dashed line).

The optimal price is more than previous estimates of optimal water prices. The MUC estimated here suggests that existing water prices should be $19 per one thousand gallons more than existing water prices, which is approximately 80 percent greater than the current level. Moncur and Pollock (1988) found that in Hawaii the scarcity value was $1.04 per one thousand gallons and Ipe and Bhagwat (2002) estimated that in Chicago it was \$2.39 per one thousand gallons. I suspect that my estimate is greater than these since there is increased water scarcity in the test case than in Hawaii and Chicago. However, the estimate is similar to that of Martin et al. (1984) who found that Tucson rates should increase by 58 percent to reflect scarcity pricing. Scarcity in Tucson and Albuquerque is more similar than Albuquerque and Chicago or Hawaii.

The MUC is sensitive to the population growth rate since pumping costs increase with population. Recall that the MUC is the marginal net benefit of the next consumption unit so that as costs increase, MUC decreases. In the case of slow population growth (see Section 3.4.2) the MUC increases since MC is less. The difference in MUC under the base and slow growth case is 0.10 percent. In the fast growth case, where MC increases and MUC decreases; the difference is -0.30 percent.

To place the optimal price in context, I compare \$7,782 to recorded prices from water transfers in the Western U.S. Brewer et al. (2007) review water leases and sales in the 12 western states and consider transfers between agriculture and urban users. Specifically I consider the sales data they report since a sale means that the buyer has in perpetuity the right to use the transfered water. I make this comparison because in the optimal price, the MUC means that there is a cost placed on society *in perpetuity* from not being able to use in the future the acre-foot used today. Further, the optimal price informs the manager about the price he or she should be willing to pay to acquire new water resources instead of pumping from the aquifer. In Table 3 of Brewer et al.'s report [p. 24], the mean water sales price for transfers in the West from 1987 through 2005 is listed. The 2005 price, \$8,912 per acre-foot, which can be considered the price of the next best alternative to groundwater, is slightly greater than estimated price in this paper. This implies that until the optimal price reaches \$8,912 the manager may be better off using groundwater than purchasing additional water rights.

In 2008 the ABCWUA transfered 2.19 acre-feet from an agricultural user for a price of \$8,000 per acre-foot (Hahn, 2009). The optimal price in the simulation at the beginning of 2008 is \$8,154, which is greater than the price ABCWUA actually had to pay for the 2008 transfer. This means that the transfer was a good deal for customers represented by ABCWUA because the acquisition price is less than the optimal price. Thus, the optimal price path is a schedule of prices that, in addition to optimally allocating groundwater, acts a reference point to which the ABCWUA may base the price for new water acquisitions.

Consider now a numerical example of how an individual customer will likely respond to increased water prices. Assume a conservation minded person has installed a low-flow shower head that flows at 2.5 gallons per minute and that the individual takes a ten minute shower. Under SQM, p_0 from Table 3.2, the individual's cost of the the ten minute shower is \$0.13. With optimal pricing the conservation-minded individual would pay, in simulation period one, \$0.50 per ten minute shower. A non-conservation minded individual with a high-flow shower (5 gallons per minute) would experience a price change from \$0.26 to \$1 for the equivalent ten minute shower. How would people respond? Assuming the elasticity estimated earlier is representative of the average customer response, -0.58, the conservation and non-conservation individual would conserve more by limiting their showers to three minutes. The non-conserving person could install a low-flow shower head then have a six-minute shower under the new price structure for the same per shower expenditure.

Inherent in this logic is the question of income inequity. Is scarcity value pricing equitable? How are low and fixed income users affected? Griffin (2001) previously addressed this criticism:

> "Water bills should be perceived as what they are: requests for payment for a valued, delivered service . . . rates do not have a comparative advantage in correcting income inequity and such attempts can be damaging

> to both efficiency and conservation objectives.” (p.1336)

From Figure 3.2, recall that OCM reduces aquifer height much less than SQM. Griffin’s statement is true in this context since the OCM aquifer height impact is less than SQM, water prices less than the OCM level create too much resource use and are thus inefficient.

3.4.4 Impacts

I noted earlier that the water managers have a two-fold predicament, increasingly scarce water resources and infrastructure that is near the end of its economic life. The manager faces this conundrum while trying to do what is best for society, which I quantify as social welfare. Table 3.3 summarizes these impacts at the end of the simulation under the status quo and the optimum for the three population growth cases.

Table 3.3: Simulation Impact Results Summary for SQM and OCM with Three Population Growth Possibilities in Year 2045

Impact	Measurement	Units	SQM	OCM Base	OCM Slow	OCM Fast
resource	aquifer height	feet above sea level	4,884.1	4,905.7	4,906.1	4,904.6
behavior	monthly pumping	acre-feet	5,911	5,389	5,341	5,528
social welfare	net benefits	millions of dollars	9,059	7,834	7,212	9,636
water utility	profits	millions of dollars	20	7,820	7,198	9,622

The resource and behavior impacts in the table, consistent with Figures 3.2 and 3.3, show that the optimal pricing program mitigates scarcity by reducing the amount of monthly pumping, which in turn minimizes the extent to which the aquifer height declines. The table shows the fact that customer behavior is modified since monthly production is much less, 522 acre-feet, under the optimal program.

The social welfare impact shows a tenuous result. *Prima facie* the status quo program is better for society since net benefits are $1.2 billion greater than the optimal program. The important caveat is that the optimal program maximizes net benefits subject to the resource constraint yet the status quo does not. Thus, a gain in social welfare of $1.2 billion comes at a resource cost of 21.6 feet of aquifer height.

The last part of the manager's predicament is to update water infrastructure. Optimal water pricing mitigates resource scarcity *and* generates sufficient revenue to deal with capital funding needs. Table 3.3 shows this by comparing utility profits under both management programs. The optimal program simulates utility profits at $7.8 billion while the status quo program estimate is $20 million. This result suggest that OCM may offer a "two-for-one" solution to the manager's two-fold predicament. Recall that Cromwell et al. (2001) suggests that within 30 years, capital expenditures must increase by a factor of 3.5 to meet infrastructure replacement challenges. The utility profits result, interpreted qualitatively since it is from a simulation, suggests that OCM offers the manager a mechanism to generate revenue for infrastructure replacement.

3.5 Conclusion

This paper uses optimal control theory to create a framework for analyzing the impacts of collecting the scarcity value of water. I simulate that framework over a 40-year time horizon to identify impacts to the resource, the water utility, and to society. The model relies on hydrologic parameters, aquifer height, population, water production, and total water revenues from Albuquerque, New Mexico. I find that existing water prices are 20 percent of the level where MUC is captured, which is a $19 per one thousand gallons increase.

The optimal pricing program, which collects scarcity value in the form of the marginal user cost, preserves at least 21.6 feet of aquifer height when compared to a status-quo management program. Net social benefit are less under the optimal program ($7.8 billion) compared to the status quo ($9 billion) because of the resource constraint; the status quo is not subject to a resource constraint. In the simulation, the absence of the optimal program finds that nearly all net benefits accrue to water customers and the water utility generates significantly less revenue than it could otherwise. This result suggests that, to the extent the simulated utility is similar to other water utilities, without optimal water pricing utilities may not be able generate enough revenue to invest in capital improvements projects like water infrastructure replacement.

Optimal water pricing is not without its critiques. I recognize the need for a change in regulation to accommodate a pricing program that incorporates the scarcity value of water. As the institutional modification argument develops, this paper suggests at least three reasons why regulatory barriers should be modified. Optimal water pricing preserves aquifer height, generates revenue for capital projects, and uses price to modify consumer behavior.

The framework uses an unconfined, groundwater aquifer model. Recently the ABCWUA started using surface water diversions to supplement the water supply through the San Juan Chama Drinking Water Project.[15] One extension to this framework is to build in a surface water component and to make the recharge parameter stochastic. This would add another layer of realism to the model and shed light on water prices in times of drought. The cost function that I estimate could

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[15] The San Juan Chama Drinking Water Diversion Project was completed in December, 2008 at which point the Authority began using surface water to augment water supplies.

be made richer through well-specific, pump-specific estimation. At any one time, there are between 86 and 109 wells used for the Albuquerque groundwater water supply. Another extension is to estimate a translog-cost function where each well is responsible for a share of production as opposed to a single point of reference for the aquifer height measurement that is used.

I noted in the beginning of the paper that in terms of water resource management, the economists' long-sounding battle cry has been higher prices. To that argument this paper contributes: scarcity value pricing efficiently allocates a scarce groundwater resource, offers water managers a means whereby capital improvement projects may be more easily attainable, and promotes a conservation ethic. The regulatory problem is that excess revenues are prohibited for the water utility, thus framing scarcity pricing in the context of infrastructure replacement may be more palatable. The simulated world that I model can in fact get a "two-for-one" out of a single policy prescription.

Chapter 4

Investigating the Water Conservation Decision

4.1 Introduction

Water resources are increasingly scarce. Climate change and the increased occurrence of drought, among other things, suggest that an already scarce resource is becoming more so (Saunders et al., 2008). In tandem, population growth suggests that residential water demand will continue to increase.[1] These two factors alone suggest that water is increasingly scarce yet there are others that compete for limited supplies. Water users with environmental, recreational, agricultural, cultural, and other demands have a stake at the water resource decision table. For the urban water manager, one way to deal with scarcity is to promote water conservation amongst the customer base. This paper investigates the water conservation decision experimentally.

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[1] The Census Bureau forecasts the Western U.S. population to increase 45% over the years 2000 through 2030. `www.census.gov` last accessed 18 April 2009

Water, either from the surface or aquifer, is a common pool resource (CPR), a specific public good classification. Gardner et al. (1990) list four necessary conditions that identify a CPR. Condition one, rivalry, states that the flow of resource units are subtractable, that units consumed by an individual are generally not available for consumption by another. Condition two, non-excludability, states that two or more individuals harvest the resource. Conditions three and four state that the individuals' optimal strategies are not Pareto optimal (Budescu et al., 1995), which means that increased consumption by one person decreases the well-being of another. Budescu et al. explain conditions three and four as the CPR dilemma, which is essentially a conflict between collective rationality ("cooperation") and individual rationality ("competitive behavior") since a CPR is non-excludable.

Conserved water satisfies these conditions. Non-conserving customers may free-ride on conserving-customer efforts. This paper investigates the water conservation decision by experimentally testing the role of group size, information, and communication at mitigating free-rider behavior thus reconciling individual and collective rationality.

From the time Gordon (1954) first observed that over exploitation of a CPR leads to the "tragedy of the commons," CPR exploitation and measures to arrive at the social optimum have been a popular theme in the economics literature. Given the difficulty in gathering data necessary for addressing exploitation of the CPR, experimental economics has been a useful tool for the analysis. Studies range from those dealing with a single-stage framework (Walker et al., 1990; Walker and Gardner, 1992; Andreoni, 1993; Keser and Gardner, 1999) to those concerned with the role of uncertainty in a dynamic framework (Moxnes, 1998; Budescu et al., 1995). Time externalities (Herr et al., 1997; Chermak and Krause, 2002; Fischer et al., 2004) and mitigating the effects of over exploitation through cooperation (Mason and Polasky, 1997; Mason and Phillips, 1997; Tarui et al., 2008) have also been studied. This paper contributes to this literature by investigating a residential customer's water conservation decision experimentally in a single stage, public goods framework.

The motivation for this research is to find factors that promote water conservation and that may be feasibly implemented by an urban water manager. To that end I consider three experimental treatments. The first consideration is the level at which conservation should be targeted. Does it make a difference if the manager encourages conservation at the neighborhood level or the city-wide level? The consumer may act differently if he or she feels social pressure from within the neighborhood to conserve versus social pressure spread out over the entire city. Further, the consumption decision of the individual may be impacted more by observations of the neighbor's water-use than that of residents in some other part of the city. Thus, the first treatment is group size. Second, the role of reciprocity and social norms may promote conservation. An informed treatment sheds light on the extent to which observed consumption of others impacts one's own consumption. Finally, conservation may be impacted by communication. This treatment investigates how communication with group members enters the water-use decision.

The theoretical model is a voluntary contributions mechanism modified to capture a voluntary *conservation* mechanism. I develop the optimal individual consumption decision in Section 4.2. Section 4.3 discusses the protocol, procedures, and treatments for the experiment. Section 4.4 presents experiment results and conclusions are in Section 4.5.

4.2 Conservation Model

This section models participant incentives in a voluntary conservation mechanism. Based on the model, I identify possible strategies a participant might follow and consider which combination of strategies constitute stable and unstable equilibria.

4.2.1 A Voluntary Conservation Mechanism

Consider a hypothetical surface water allocation in an urban water system. In each period, S units of water are available to the group of N consumers. There is no carryover of S between periods. Storage is not an option. The single-stage framework is analogous to considering a yearly allocation from which consumers make a water consumption decision. S provides for water use for the consumers and is a public good in the sense that it may recharge a groundwater aquifer that provides for future consumers' water needs, and is used to meet the demands of environmental, agricultural, cultural, and recreational interests. These benefits accrue outside of the urban water system to which the N players belong, however, the urban consumers benefit from S as a public good at the rate α dollars per water unit where $\alpha > 1$ is the public good to payoff conversion factor. Thus, αS is the dollar value of the surface water public good.

The urban consumers benefit from the public good but they also make private water use decisions. Each consumer i makes a private water consumption decision q_i to maximize their benefits. The sum of consumption decisions over all consumers, $\sum_{i=1}^{N} q_i$, reduces water that is available for the surface water public good. Thus, the value of the public good becomes:

$$\alpha \left(S - \sum_{i=1}^{N} q_i \right), \tag{4.1}$$

which can be thought of as the value of surface water conservation. Note that i indexes the participants in the group. Implicitly, then, the consumption decision q_i is also a conservation decision.

Participants can be of three consumer-types: low, medium, and high. Low types value private water use less than medium types who in turn value private water use less than do high types. With a normalized water price equal to one, and assuming a downward sloping individual water demand curve, participant i's consumption benefits are:

$$B_i^k(q_i) = -\frac{a}{2}q_i^2 + b^k q_i, \tag{4.2}$$

where the vertical intercept term b^k indexes consumer types: $k = l, m, h$ for low, medium, and high respectively. Benefits by consumer type vary in absolute magnitude but not in elasticities since I assume these are net benefits.

In each period participants make consumption decisions recognizing that private consumption has an impact on the water-conservation public good. Per-period profits of consumer i, which are the payoffs earned by round, are:

$$\pi_i^k = -\frac{a}{2}q_i^2 + b^k q_i + \alpha \left[\frac{\left(S - \sum_{i=1}^{N} q_i \right)}{N} \right], \tag{4.3}$$

where the last term on the right-hand-side is the fraction of the public good that benefits the individual player. Participants get a private benefit from consumption as well as the N^{th} part of the conserved public good, which increases with conservation. The consumer's task is to optimally choose water consumption q_i, which is the decision that maximizes equation (4.3), and is:

$$\pi_{i_{q_i}}^{k} = 0 \Leftrightarrow -aq_i + b^k - \frac{\alpha}{N} = 0. \tag{4.4}$$

The optimal consumption decision is found by solving equation (4.4) for q_i^*.

Before doing so, however, rearrangement of equation (4.4) provides useful insight.

$$-aq_i + b^k = \frac{\alpha}{N}. \tag{4.5}$$

The left-hand-side of equation (4.5) is the marginal benefit of private consumption and the right-hand-side is the private marginal benefit of conservation, which is the private marginal benefit of the public good.[2] At the margin, the individual should

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[2] Note that external benefits to, for example, recreational users, do not appear in the individual's optimization problems as is standard for public goods and externalities.

equate marginal benefits of private consumption to private marginal benefits of conservation. If marginal consumption benefits are greater than marginal conservation benefits, then the individual should consume more; otherwise the individual should consume less.

Table 4.1: Individually Optimal Consumption Decisions

		Optimal Decision	Optimal Decision
Player Type	b^k	$N = 3$	N=12
low	2.25	8	10
medium	2.5	9	12
high	2.75	10	13

$a = 0.2$, $\alpha = 2$

The individually optimal consumption decisions in Table 4.1 is calculated as:

$$q_i^* = \frac{b^k}{a} - \frac{\alpha}{aN}. \tag{4.6}$$

where the parameters b^k, a, and α were chosen by numerically testing the experiment so that the expected participant payment was \$30. The optimal decision for two possible group sizes are given in Table 4.1. Conservation occurs if the player chooses to consume an amount that is less than the individually optimal decision.

4.2.2 Strategies and Decisions

I assume there are four possible strategies a consumer may choose to follow given the optimal solution. Strategies are related to behavior type to which there is a corresponding consumption decision. There is a sub-optimal strategy, a non-optimal strategy, one that is individually optimal and one that is socially optimal. Since the model is at the decision level of the individual, assume that the social optimum is to consume zero units. The strategies are shown in Table 4.2.

Table 4.2: Consumption Decisions and Strategies

Strategy	Decision	Behavior	Strategic Consideration
max consumption benefits (sub-optimal)	$\frac{b^k}{a}$	incognizant	public good bears no impact on decision
race for the resource (non-optimal)	$\frac{S}{N} + \epsilon^*$	dominating	consume resource before someone else does
max consumption and conservation benefits (individually optimal)	$\frac{b^k}{a} - \frac{\alpha}{aN}$	competitive	motivated self-interest individual rationality
max conservation benefits (socially optimal)	0	cooperative	coordination collective rationality

*If all race for the resource the q's are prorated, the max any player could get is is ϵ above average water per consumer.

The first strategy in the table is for an individual whose behavior is incognizant to the public good. A consumer of this type is one who makes a water consumption decision that does not consider his or her own benefit from the public good. The decision is sub-optimal since it is made solely by maximizing private consumption benefits and not considering conservation benefits. This ignorance could be due to a number of factors. It may simply be the case that the consumer is not aware of how conservation contributes to the public good and thus fails to recognize that the N^{th} part of total conservation increases his or her profits. It could also be the case that the consumer does recognize that there exists a conservation public good but chooses to ignore it.

The race for the resource strategy is one that reflects dominating behavior. The decision is non-optimal since too much individual consumption leads to negative marginal benefits. From equation (4.3), diminishing benefit from private consumption means that for each consumer type, there is a level of consumption where the marginal benefit of private consumption is negative. The consumer who follows this strategy is one whose motives are not profit maximizing. The motivation is simply to consume more of the resource than any other consumer or to consume the resource before someone else does. If all participants follow this strategy then the cumulative consumption decision exceeds S. Participant decisions are prorated per the ratio of S to cumulative consumption so that the most a participant actually gets is an ϵ greater than average use, which is determined by the ratio.

Strategy three is individually optimal. This is the strategy for which private marginal benefits of consumption equal private marginal benefits of conservation, which is the public good. That is, this decision ensures the individual consumer the maximum benefits from consumption *and* conservation which make it an individually rational decision if coordination breaks down.

The final strategy is socially optimal since the consumption decision is zero, which is analogous to assuming water use above a basic needs level.[3] Since the model is at the individual decision level, conservation is present for any consumption level less than the individual optimum. Thus a consumption level of zero constitutes the extreme conservation decision. If there is no consumption then there is no S subtraction. Because $\alpha > 1$, total group value is maximized when S is maximized. The strategy is to maximize benefits from conservation and none from consumption. Per Budescu et al.'s definition, this behavior is cooperative since it requires coordination and collective rationality. It is also where the CPR dilemma is most apparent. If

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[3] The restrictive assumption of the social optimum equal to zero units is analogous to considering a customer's water decision above a minimum, necessary threshold amount. This assumes that basic water needs are met and that the participants decision is for units above the critical, necessary minimum.

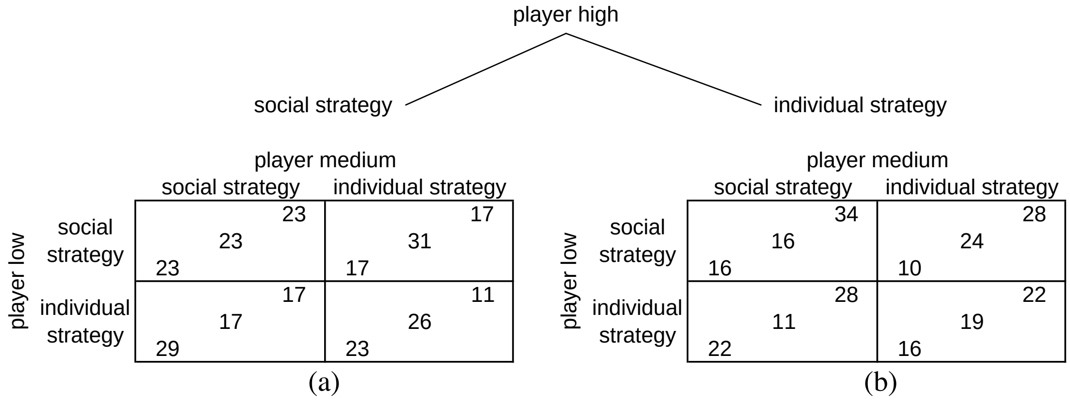
all players follow a cooperative strategy then each player gets $\alpha\frac{S}{N}$ in benefits. If one player defects from the coordinated strategy then the defector is better off and earns profits per equation (4.3), those following coordination are worse off and get $\alpha\frac{S-\sum_i^N q_i}{N}$. Herein lies the incentive to defect from the coordinated decision and the clash between collective and individual rationality, a theme treated further in the next section.

4.2.3 Cooperative and Non-Cooperative Equilibria

I now turn to a numerical example of the individually optimal and socially optimal strategies shown in Table 4.2. With a numerical example, I identify the cooperative equilibrium and the Nash, non-cooperative equilibrium.

The example relies on the parameters used in the small group experimental treatment discussed in Section 4.3 with $N = 3$, $\alpha = 2$, and $S = 34$. The parameters of the net benefit function are $a = 0.2$ and b^l, b^m, b^h, equal to 2.25, 2.5, and 2.75 respectively. These yield the payoff matrix shown in Figure 4.1.

Figure 4.1: A Three-Player Two-Choice Water Conservation Game Payoff Matrix: row player payoff in bottom left, column player in top right



(a) (b)

The socially optimal strategy in this framework is for all players in the group to choose zero units of consumption. If an agreement can be reached, and all players maintain the agreement, the socially optimal solution returns a payoff to each player greater than the outcome from all players choosing the individually optimal decision. However, the temptation to defect from the agreement may return to the defector payoffs greater than the coordinated effort.

Suppose a coordinated agreement is reached by the three players in the group in which each player consumes zero units. Player high's decision to hold to the agreement places the analysis in the (a) matrix of the figure. Since player low (row player) and player medium (column player) also hold to the agreement, and each player earns 23. This cooperative equilibrium is an unstable point. The temptation to defect threatens the equilibrium's stability.

Player low has a six-unit incentive to defect. If players medium and high maintain the social strategy, player low can increase his payoffs to 29 by choosing the individual strategy. This, however, reduces the payoffs for the medium and high player to 17. Player medium and high also face the temptation to defect. Player medium earns 31 by defecting when the others do not and player high could earn 34 by defecting while the other two maintain the agreement.

The incentive to defect illustrates that the individual strategy is the dominant strategy for each player. If all follow the dominant strategy the Nash, non-cooperative solution obtains. The payoff cell becomes matrix (b) SE. Each player's payoffs are less than the cooperative solution, matrix (a) NW, however each player does not experience the same degree of mis-fortune. Player low suffers the greatest and player high the least.

I now turn to the protocol, procedures, and treatments that are used in a water conservation context of the experiment to investigate the role of group size, information, and communication at promoting reduced-use.

4.3 Protocol, Procedure, and Treatments

Participants were recruited from among students and staff at the University of New Mexico (UNM) and adults from the greater Albuquerque, New Mexico population using advertisements posted on Craig's List and email list-serves.[4] A total of 45 participants completed the experiment. Table 4.3 shows the treatment variables by session which were conducted. Due to time constraints, round 5 in each session was omitted however excess time allowed us to conduct an additional round in session 1. Each session was conducted in English.

Table 4.3: Treatment Variables by Session

Session	Communication	Group Size	Uninformed	Informed
1	no	3	rounds 1 – 4	rounds 6 – 10
2	no	12	rounds 1 – 4	rounds 6 – 9
3	yes	3	rounds 1 – 4	rounds 6 – 9
4	yes	12	rounds 1 – 4	rounds 6 – 9

Participants were invited to participate in one of four sessions, approximately one-hour each, held on separate evenings in one of the economics classrooms at UNM. They were seated in such a way that no participant could readily look at the answers provided by another. Participants were told that they could earn at least $15 for participating and that the average participant payment was $30. Three participants received $15 due to not being able to participate since some sessions had more participants arrive than there were spaces available. The average payment was $37 per participant.

The participants' primary task was to make a water consumption decision. Water consumption and water conservation convert to dollars, according to equation (4.3).

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[4] http://albuquerque.craigslist.org last accessed 30 April 2009. Summary descriptive statistics of participants shown in Table 4.4 in Section 4.4.

Participants were randomly assigned to a group that shared a "Public Water Bucket" containing water supply S. Each participant decided how much water, q_i, from the public bucket they would like to place in their "Private Water Bucket." Participants were told that water remaining in the public bucket at the end of the round doubles and converts to an equal dollar payment for each group member.

I announced at the beginning of the experiment session that at the end of the session two random draws from a bingo cage would determine which two rounds constitute payment; payoffs for the two rounds would be summed. This gave the participants an incentive to play each round as if that round was the one for which payment would be made. Participants were not told the number of rounds in each session. At the end of each round participants recorded their consumption decisions and handed it to one of the experimenters. An experimenter seated at a computer in another room recorded the data and returned to participants the decision sheet with remaining water units in the public bucket and water that the participant gets to keep. If demand was greater than supply, individual decisions were prorated by the ratio of supply to demand. The returned decision sheet contained the payment the participant would earn if that round were selected.

Each participant was given a packet of information. The packet included a "Returns from the Public Water Bucket." This handout showed participants the payment that each group member would receive for each possible amount remaining in the public bucket. It is calculated by doubling each water amount then dividing the sum by the total number of players in the group thus the marginal per-capita return (MPCR) from the conservation public good is $\frac{2}{N}$ so that it was $\frac{2}{3}$ for small groups and $\frac{1}{6}$ for large groups.

The packet also includes a "Returns from the Private Water Bucket." There are three versions of this handout that correspond to the three user-types that are discussed in Section 4.2. These returns are calculated using $-\frac{a}{2}q_i^2 + b^k q_i$ from equation

(4.3) where $a = 0.2$ and b^l, b^m, b^h, are set at 2.25, 2.5, and 2.75 respectively. Participants see only their packet of information and are not told that private returns vary. Each group in the small group treatment included one participant of each player type. In the large group treatment each group included four participants of each player type.

4.3.1 Group Size Treatment

The group size treatment, small ($N = 3$) and large ($N = 12$), was administered in separate sessions. The motivation is to find out if water conservation is promoted more by dealing with it at a local, neighborhood level or at a city-wide level. Following Andreoni (1988), groups are not reconstituted between rounds. Doing this allows for participants to experience learning behavior from other group members while remaining anonymous. In a water conservation context it is useful since it is analogous to living in the same neighborhood as other homeowners, observing their water use behavior, but never actually meeting the neighbors.

The group size treatment has implications for the MPCR since it is $\frac{\alpha}{N}$. The small group MPCR is 0.67 while the large group MPCR is 0.17. However, the large group treatment is scaled from the small group treatment. S for the small group is 34 and for the large group is 136. This is analogous to there being a fixed water supply where benefits from the conserved water public good are the same for participants in either the small or large group treatment. There is an extant literature (Isaac and Walker, 1988a,b; Isaac et al., 1994) that finds voluntary contributions to the public good increase with group size yet that result is sensitive to the MPRC. Further, Isaac et al. note that the group size effect diminishes with the ability to organize a group coalition. The group size treatment employed here is slightly different in that the public good is conservation of a resource, not a contribution to a public good. Per-unit benefits to the individual from the public good are identical for both treatments.

4.3.2 Information Treatment

One in-sample treatment, informed–uninformed, presents participants with information about the consumption decision of other players in the group. In each session, the first half of the session is the uniformed treatment with the informed treatment in the second half. Information about players' prior round consumption was displayed on a bar graph. In the small group treatment the information is provided to the participant with the decision-round sheet, in the large group treatment information chart is displayed on an overhead projector. The information treatment parallels the fact that a residential water user may see the outdoor consumption decision of his or her neighbors and make a private water decision based on the observation of others.

The social norm effect that is captured by the information treatment is not new. Fehr and Gächter (2000) found that sanctions taken against free-riders was a primary consideration in participants' decision not to free-ride and that sanctions could come in the form of emotional frustrations from the group. Then Fischbacher et al. (2001) found that experimental participants can often be characterized as 'conditional cooperators' since a private contribution decision is a function of the group's decision, a finding found again in Fehr and Fischbacher (2004). More recently Charness and Dufwenberg (2006) found that, on the part of the experimental participant, the desire to live up to the expectation of the group was a major consideration in coordinated behavior. These findings suggest that for the water conservation problem social norms and reciprocity may mitigate conservation free-riding.

4.3.3 Communication Treatment

The communication treatment implements a group "discussion board." At the beginning of each round, if a participant chooses to communicate, he or she writes on a piece of paper a note that the experimenters photocopy onto a discussion board and then distribute to the rest of the group. No identifying information is allowed in the communication. Since conservation is voluntary, free-riding behavior is legal. This means that the communication is non-binding, no penalties or punishments are enforced or allowed. Participants can simply communicate using the discussion board with other group members. In a water conservation context the discussion board simulates, for the small group treatment, a community newsletter that may discuss water use or issues. For the large group treatment, the discussion board simulates a newsletter that may be included with a customer's water utility bill. Communication of this form may appear futile at promoting conservation, however, researchers have found it to increase contribution rates in public goods experiments.

Isaac and Walker (1988b) found that communication clearly increases provision of a public good. Their experiment allowed participants to communicate face-to-face for four minutes prior to making the contribution decision. In this exchange, participants could speak freely about anything except their private information in the experiment. The result was that the trend for mean contributions increased when communication was allowed. Palfrey and Rosenthal (1991) find a similar conclusion, their experiments suggest that communication increases the group's ability to coordinate efforts. More recently Bochet et al. (2006) investigated communication in the presence of punishment to which they found that face-to-face communication improves contributions more than punishments. Their next best communication alternative was a chat-room scenario where participants read comments from group members over a computer. The discussion board closely parallels the chat-room type set up since communication is within the group and anonymous.

4.4 Data, Results, and Interpretation

This section discusses the data gathered in the experiment, the results, hypothesis testing, and interpretation of results.

4.4.1 Participants and Data

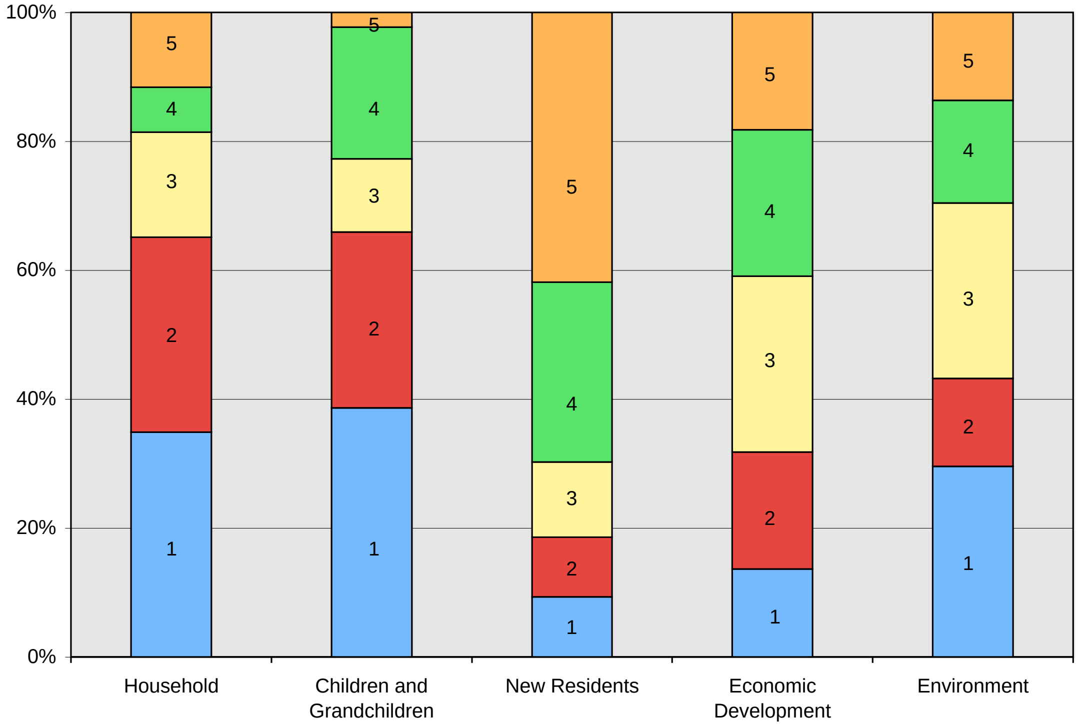
Table 4.4: Survey Descriptive Statistics

Variable	Mean or percentage	Min.	Max.	S.D.
Survey ($N = 45$)				
Age	27.9	18	70	12.5
Female	49			
Renter	58			
UNM Student	76			
Education*				
Less than High School	2			
High School	18			
Some College or Associates	59			
Bachelors	14			
Masters or equivalent	9			
Doctor or professional	2			
Income				
Less than 40,000	60			
40,000 to 60,000	21			
60,000 to 100,000	12			
Greater than 100,000	7			

*Percentages may not add to 100 due to rounding.

At the end of the experiment, participants completed a short survey. The purpose was to gather basic demographic data and to get an understanding of general water conservation preferences of the participants. Table 4.4 shows the descriptive statistics of the people who participated. There were a total of 45 participants in the experiment, 76 percent of whom were students. This most likely explains why 58 percent of the participants were renters, 59 percent had some college education, and 60 percent had income less than $40,000.

Figure 4.2: Survey Question "Reasons to Conserve by Future Use": 1 indicates most important and 5 least important



A ranking question investigated participants' opinions about reasons to conserve in which one was the most important and five the least important. The possible answers included: for your household, for your children and grandchildren, for new residents to Albuquerque, for economic development, and for the environment. Figure 4.2 illustrates participants' rankings. Nearly 40 percent ranked children and grandchildren as the most important reason to conserve closely followed by own household. New residents was the least important reason to conserve: more than 40 percent ranked it the lowest.

The conservation preference result informs urban water managers why conservation is important to consumers. The fact that the average participant indicated conservation for children and grandchildren was more important than for the household implies that consumers may not feel that the short-term water supply is as threatened as the long-term supply. Further, the average participant ranked environmental needs over economic development and new Albuquerque residents. Water managers may need to re-define management to reflect a sustainable water supply for following generations of existing customers and environmental needs, not necessarily economic development and urban sprawl.

Table 4.5 shows the descriptive statistics of the experiment. Four sessions produced a total of 369 observations. Recall that the information treatment was in-sample and that the Public Bucket units for the small group treatment was 34 and for the large group it was 136. The mean water decisions across the sessions was 9.1 which is consistent with individual rational behavior and motivated self-interest. The minimum private decision was zero which suggests that some participants followed the strategy of collective rationality. The maximum decision was 122 which fits with dominating behavior and a race-for-the-resource strategy since the maximum an incognizant player would have chosen is 10, 12, or 13 based on player type.

Table 4.5: Experimental Descriptive Statistics

Variable	Mean	Min.	Max.	S.D.
Session 1: No Communication, Small Group ($N = 81$)				
Private decision	7.9	1	16	3.5
Total group decision	23.7	12	34	6.4
Remaining public water	10.3	0	22	6.3
Player type – Low ($q^* = 8$)	6.3	1	11	2.7
Player type – Medium ($q^* = 9$)	8.0	1	16	44
Player type – High ($q^* = 10$)	9.4	5	15	2.4
Session 2: No Communication, Large Group ($N = 96$)				
Private decision	14.8	0	122	14.4
Total group decision	177.5	154	227	25.8
Remaining public water	0	0	0	0
Player type – Low ($q^* = 10$)	13.1	4	69	10.5
Player type – Medium ($q^* = 12$)	12.1	0	50	8.5
Player type – High ($q^* = 13$)	19.2	0	122	20.6
Session 3: Communication, Small Group ($N = 96$)				
Private decision	6.15	0	15	4.2
Total group decision	18.5	4	35	8.7
Remaining public water	15.6	0	30	8.5
Player type – Low ($q^* = 8$)	5.6	1	12	3.6
Player type – Medium ($q^* = 9$)	5.9	0	12	3.9
Player type – High ($q^* = 10$)	7.0	0	15	5
Session 4: Communication, Large Group ($N = 96$)				
Private decision	7.4	0	20	4.8
Total group decision	88.6	55	123	26.34
Remaining public water	47.4	13	81	24.8
Player type – Low ($q^* = 10$)	5.0	0	10	3.6
Player type – Medium ($q^* = 12$)	8.0	0	13	5.0
Player type – High ($q^* = 13$)	9.2	0	20	4.8

Conservation behavior was present in Session 1, 3, and 4 since the mean private water decision is less than the individually optimal consumption levels given in Table 4.1. Although the pure socially optimal strategy was not reached, some coordinated behavior existed which implies that participants did not act completely out of self-interest. The mean private water decision in Session 2 indicates that there was at least incognizant behavior present although it is more likely the case that dominating behavior was present since the mean private decision is greater than 14, the maximum incognizant player decision. The clear strategy of Session 2 was race-for-the-resource behavior.

The conservation results are uniform across the heterogeneous users in the experiment, with varying player types conservation is observed in each session except Session 2. High player types in every session had the highest average consumption and low player types had the lowest. Using the decision ratio, constructed in the next section, the low player types demonstrated the greatest amount of conservation in Sessions 1 and 4. The medium player types conserved the most in Sessions 2 and 3.

Now I consider the results by session rounds and treatments.

4.4.2 Deconstructing Participant Decisions

The extent to which participants exhibit conservation behavior is considered using a decision ratio (DR). The DR is the ratio of the private water decision that participants made in the experiment to the individually optimal decisions from Table 4.1. The following relationships hold.

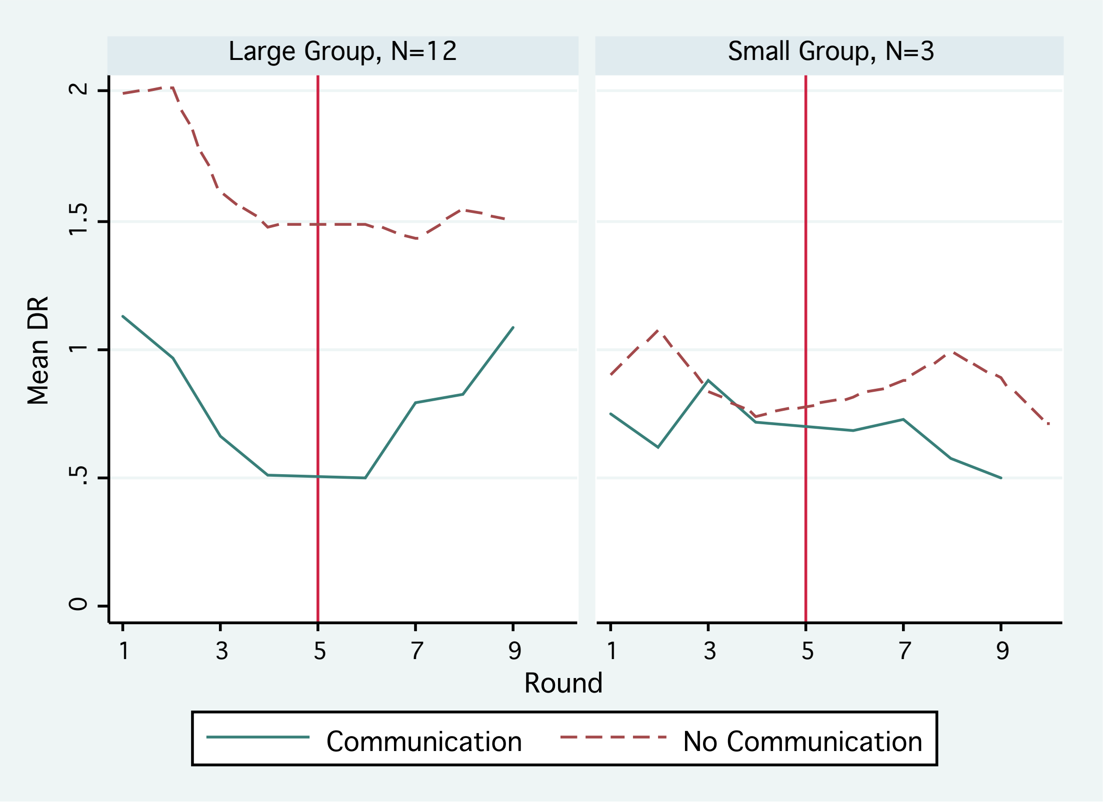
$$\begin{array}{llll} \text{DR} & = 0 & \Rightarrow & \text{social optimum, collective rationality} \\ & < 1 & \Rightarrow & \text{some conservation, coordinated behavior} \\ & = 1 & \Rightarrow & \text{individual optimum, individual rationality} \\ & > 1 & \Rightarrow & \text{dominating or incognizant behavior} \\ & & & \geq 1.1 \rightarrow \quad \text{dominating behavior, small group} \\ & & & \geq 1.4 \rightarrow \quad \text{dominating behavior, large group} \end{array}$$

Figure 4.3 shows the mean DR by round and by group size. The left panel is the mean DR result for the large group size and the right panel is the result for the small group size. The figure shows that complete collective rationality was not observed, the mean DR never reached zero. However, recall from Table 4.5 that for three sessions conservation was observed. The figure shows this as rounds where the DR is less than one, which suggests that there was some coordinated behavior and not purely motivated self-interest.

The difference in mean DR results within group size is primarily due the role of communication that is illustrated by the difference between the dashed and solid lines in both panels. For the large group size, when communication is not present, dominating behavior was the result in each round. This is consistent with Isaac et al. (1994) who find that the ability to coordinate as a group diminishes as group size increases. For the small group size, the difference from communication was less. Round two, small group and no communication, is the only point in the small group treatment where conservation was not observed since the DR is less than one in all other rounds. With the exception of round four in the small group treatment, the mean DR is always less with communication. This suggests that communication plays a role in promoting coordinated behavior and conservation.

The information treatment provided participants a bar-chart that displayed individual group member decisons in rounds six through nine. Round five, which was

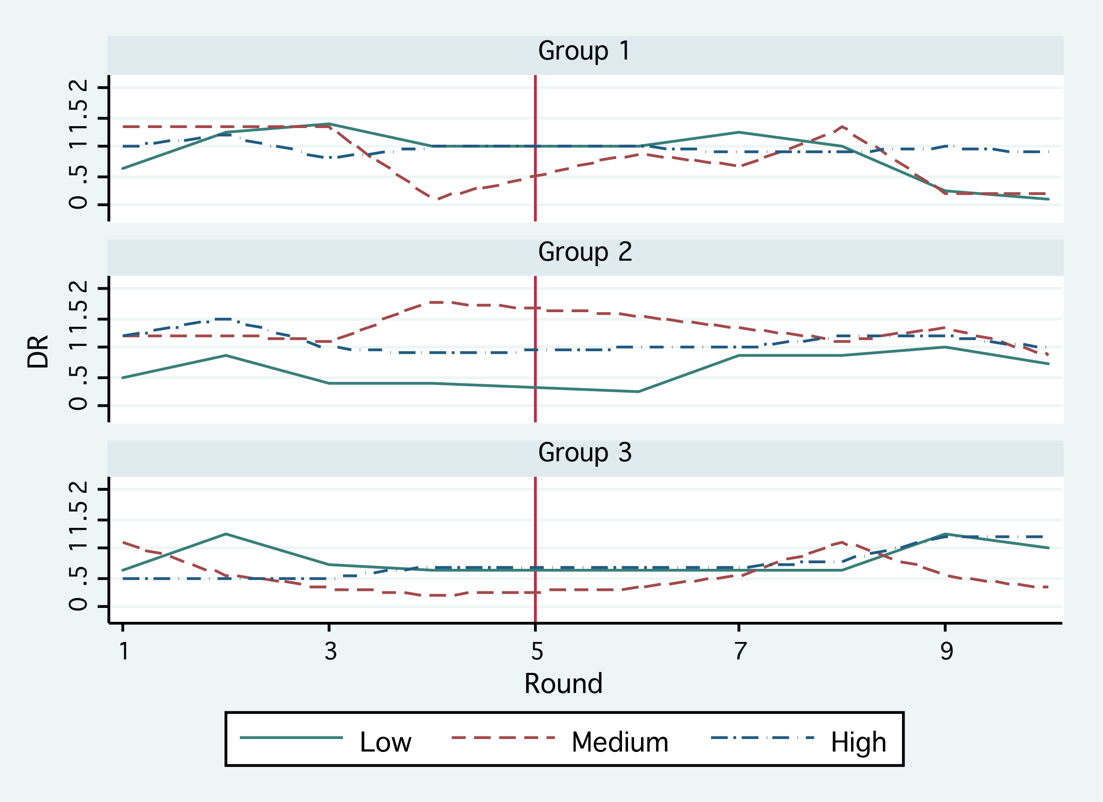
Figure 4.3: Mean Decision Ratio (DR) by Rounds. Vertical line indicates round in which information became present.



omitted in the experiment, is an information reference point on each panel. The information results vary. I consider the participants' DR for each session to ascertain the effect of information and begin with the small group treatments; Session 1 and 3.

Figure 4.4 shows the participants' DR for each group. The figure is for Session 1, which is a small group treatment without communication. Each line represents the DR of an individual player and in this figure is labeled by player type. The vertical gray line indicates the point at which information became present. For these participants, the DRs converged when information was present. The DR of the high player types, the dotted lines, were not impacted by information as much as other player types. Medium player types responded the most to information; their DRs

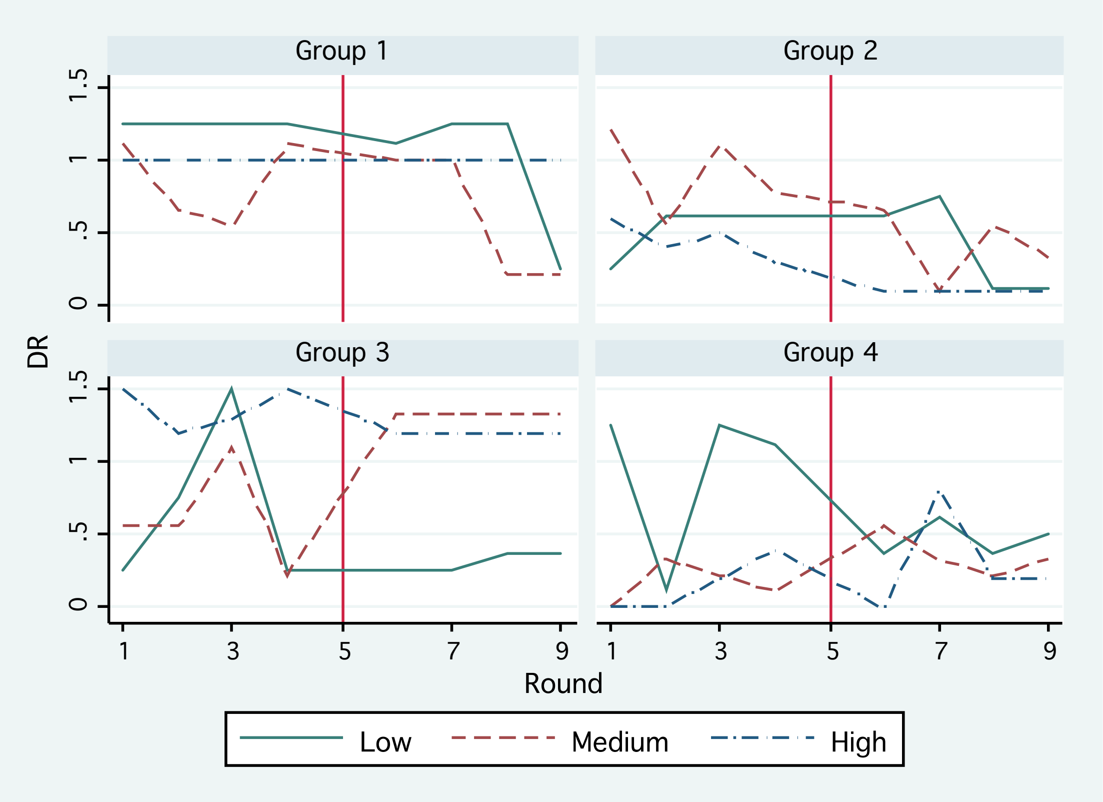
Figure 4.4: Decision Ratio (DR) by Rounds and Player Type: Session 1, No Communication, Small Group. Vertical line indicates round in which information became present.



changed the most from the first half of the session to the second. The low player type DRs increased with information except for the low player in Group 1 where the DR decreased.

Figure 4.5 presents the results from Session 3, which is a small group treatment with communication. These results are similar to the previous figure since the DRs with information became more closely grouped. Recall from Table 4.5 that Session 3 was the one where conservation was most observed; the mean private water decision was less than other sessions. The figure shows that this result may have been driven by Groups 2 and 4; the DR was the least for participants in these groups. Consistent with Session 1 results, the DR of player type high changed the least with information

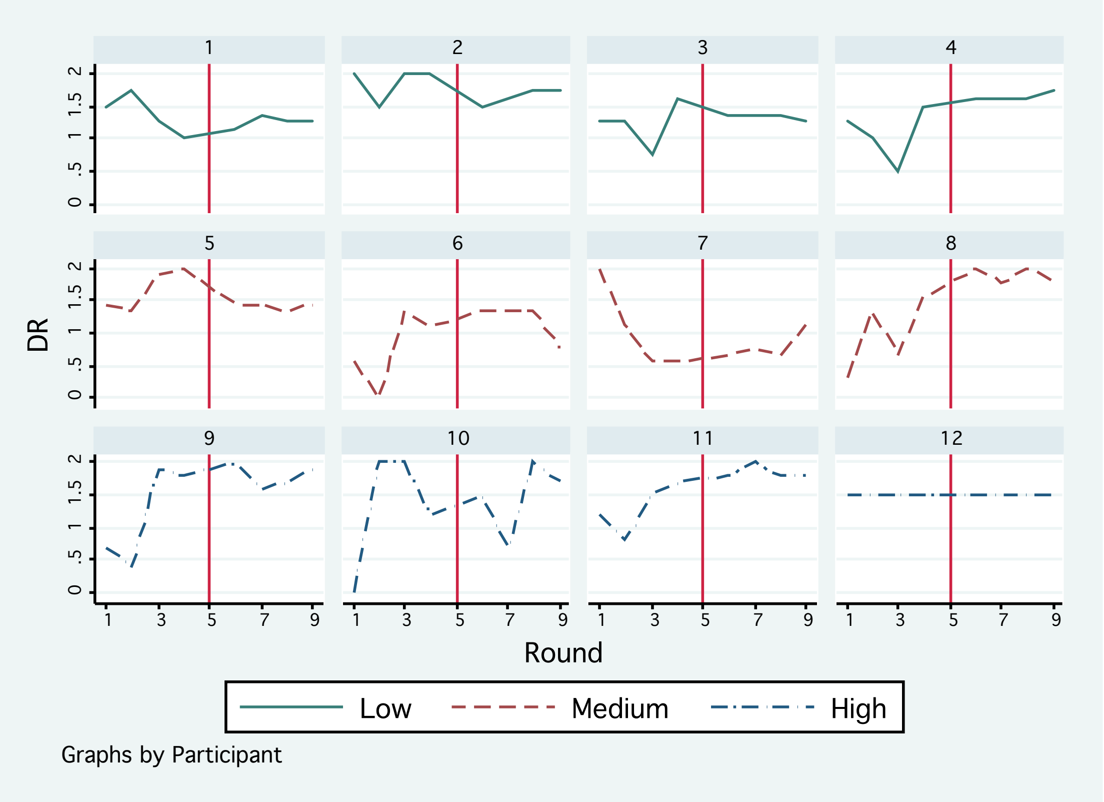
Figure 4.5: Decision Ratio (DR) by Rounds and Player Type: Session 3, Communication, Small Group. Vertical line indicates round in which information became present.



except in Group 4 where the DR increased. The DR of medium type players is mixed, some increased with information (Group 3 and 4) while others decreased (Group 1 and 2). The low player type DR in Group 3 bears out an altruistic result; the other two player is Group 3 had large DRs while the low player remained with a constant, small DR strategy. The Session 3 results illustrate how conservation on the part of some players may offset the over consumption by others, even if it is dominating behavior. The mean private decision was the least in Session 3.

The average DR in the large group treatment was greater. Figures 4.6 and 4.7 show the DR by participant since there was a single group in the large group treatment. Each row of the figures corresponds to player type; low, medium, and high

Figure 4.6: Decision Ratio (DR) by Rounds and Player Type: Session 2, No Communication, Large Group. Vertical line indicates round in which information became present.



and there were four participants of each type.

Figure 4.6 shows that there was considerable variation in the DR. The DR of some participants changed dramatically throughout the session while for others, the DR remained relatively unchanged. Recall from Figure 4.3 that the mean DR for Session 2 stabilized with the presence of information. This result is observed here in that for many of the Session 2 participants, the variation in the DR decreased with information. Further recall that the mean private decision was the greatest in Session 2. This fits with ten of the DRs illustrating incognizant or dominating behavior for all rounds and for two participants that began with conservation behavior following suit. Many of the players started with a low decision that increased over rounds.

Figure 4.7: Decision Ratio (DR) by Rounds and Player Type: Session 4, Communication, Large Group. Vertical line indicates round in which information became present.

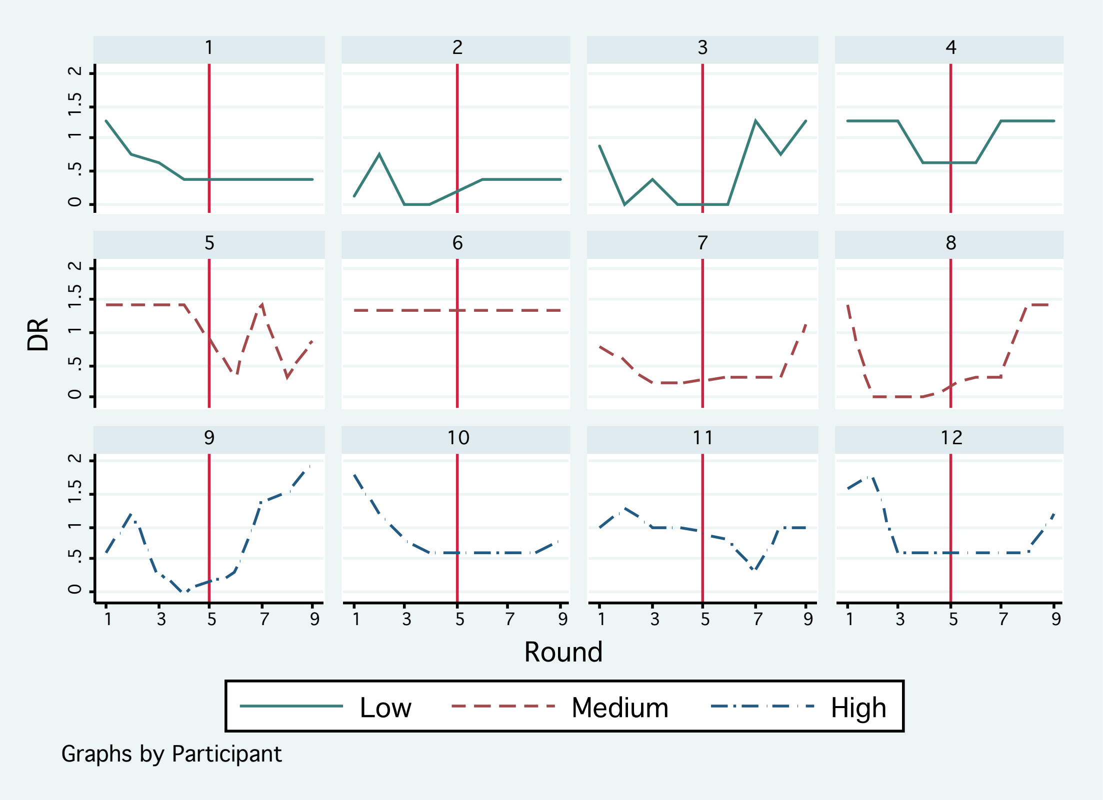


Figure 4.7 presents the results for the final session, which was a large group with communication. The participants' DR is lower in this session than in the previous large group session. Here the role of information was to stabilize the DR of four participants while for six it increased. In conjunction with the small group and information, results suggests that free-riding behavior in a small group is mitigated to a larger extent than in a large group and that information influences that result.

Participants made lower consumption decisions when communication was present. The theme from participant communication was to put less water into the private bucket. The following are a sample comments that were placed on the discussion board.

> "So are we switching to the 6-unit plan?"
>
> "We need more lower numbers guys!"
>
> "Keep your private water bucket amount (what you keep) low – we make more by having more water left in the public water bucket."
>
> "Yeah, if we all use less water we can make more. Good idea."
>
> "What happened to taking only 2 units for private bucket?"
>
> "Each of us would get $23 a round if we all took 3 water units a round, which I believe is the most we can make without cheating each other."

Not all participants submitted comments for the discussion board. However, participants generally increased their use of the discussion board as the session went on. This sample shows that players generally used communication to coordinate consumption decisions and maximize payoffs.

Based on these findings, I construct three hypotheses that are tested in the next section.

4.4.3 Hypothesis Testing and Interpretation

In this section I test the impact of the treatment variables on the DR. Since data were collected from different samples of the population, I use non-parametric methods to test the hypotheses and discuss these and the urban water implications here.

Non-parametric testing is a method to compare two distributions drawn from different samples. The treatment variables group size and communication were administered in separate sessions so that the data is from separate samples. To test the impact of these I use the Wilcoxon Rank-Sum test, where the null hypothesis is that the relative frequency of the DR distribution is identical within treatments. The information treatment was administered within a single session thus the data are from the same population. To compare distributions drawn from the same population I use the Wilcoxon Sign-Rank test, where the null hypothesis is that the DRs without information are identical to the DRs with information.

Two of the four sessions were administered with group size equal to three, two had group size equal to 12. The first null hypothesis is:

$$H_0 : DR_{small} = DR_{large}.$$

Table 4.6 shows the mean DR under each group size treatment, the hypothesis, and the z-score by which the null hypothesis is rejected. The probability that the DR is greater in the large group size is 0.69.

Table 4.6: Decision Ratio by Group Size and Wilcoxon Rank-Sum Test

Size	Obs.	Mean	Min.	Max.	S.D.	Hypothesis	z	Reject
Small	177	0.77	0	1.78	0.43			
Large	192	1.22	0	12.2	1.2			
						0.77 = 1.22	6.15	yes

For the urban water manager, rejecting the null suggests that group size does make a difference in the consumption decision. In the small group treatment the mean DR was 0.77, which implies that some conservation behavior existed. Recall that if the DR is one, the participant followed a strategy of individual rationality. The small group size suggests that participants were not being completely, individually rational and followed a strategy towards collective rationality and coordinated behavior. The mean DR in the large group size was 1.22, which suggests the average player was incognizant to the public good. For the manager, this implies that promoting conservation at a smaller group level promotes reduced water use more than at the large group level. This suggests that customers may be more likely to conserve if the problem is addressed at a neighborhood level. A city-wide approach may obviate the customer's ability to see conservation benefits and actually promote free-riding behavior.

Information was an in-sample treatment so that the data from both treatments were from the identical sample population. The uninformed half of the treatment was administered in rounds one through four, round five was omitted, and the information treatment was in rounds six through nine. The null hypothesis for information is:

$$H_0 : DR_{info} = DR_{no\,info}.$$

If information does not play a role in the participant's decision, there should be no difference between the two treatments. The mean DR for the informed treatment and the results of the Wilcoxon Sign-Rank test are in Table 4.7.

Table 4.7: Decision Ratio by Information and Wilcoxon Sign-Rank Test

Informed	Obs.	Mean	Min.	Max.	S.D.	Hypothesis	z	Reject
Yes	144	0.97	0.1	2.2	0.52			
No	225	1.03	0	12.2	1.13			
						0.97 = 1.03	-3.29	yes

Since the null is rejected, information does play a role in the participant's decision yet the mean DR for both treatments is very close to the individual strategy level. The results in the previous figures illustrate that the role of information varies. In some sessions the mean DR increases with information and in others it decreases. In the large group where conservation was present, the information treatment shows that the mean DR increased. The small group suggests that information may decrease the decision. I performed the sign-rank test for the information hypothesis on each group size. For each case, z = -2.6 for small and z = -2.1 for large, the null is rejected, however, information may be conditional on group size.

The information result has implications for an urban water manager depending on the level to which conservation is targeted. In a large group approach, information may actually increase water use whereas in the small group approach information may reduce water use. This strengthens the group size result; in a large group size, if a customer sees that lots of people are not conserving the individual may also not conserve.

Communication was administered in Sessions three and four. The null hypothesis for the communication treatment is

$$H_0 : DR_{comm} = DR_{no\ comm}.$$

Table 4.8 shows the mean DR under both treatments and the results of the rank-sum test. The greatest difference in the mean DR of all three treatment variables is in the communication treatment. Without communication, the average participant engaged in incognizant behavior since the mean DR is 1.29. Further, the probability that the mean DR is less with communication is 0.71. This result fits with Isaac and Walker (1988b) who find that public good contributions increase with communication and Palfrey and Rosenthal (1991) who find that communication increases the ability of the group to engage in coordinated behavior.

Table 4.8: Decision Ratio by Communication and Wilcoxon Rank-Sum Test

Comm.	Obs.	Mean	Min.	Max.	S.D.	Hypothesis	z	Reject
Yes	192	0.75	0	2	0.49			
No	177	1.29	0	12.2	0.49			
						0.75 = 1.29	7.12	yes

For the water manager, the communication result suggests that promoting water discussion amongst the users may decrease water use thus promoting conservation. The DR was less in the communication treatment which implies that communication may increase the group's ability for coordinated decision making. With the group size result, communication suggests that small community organization may be more effective at promoting conservation than city-wide encouragement. At the community level with communication, motivated self-interest may give way to collective rationality.

4.5 Conclusions and Extensions

Increasingly scarce water resources suggest that entities who demand water will have to make do with less. For urban dwellers this means water conservation will become a larger consideration. Thus, understanding factors that promote conservation should be of concern to urban water managers. In this paper I develop a voluntary conservation mechanism to investigate three, non-price, demand-side management tools that promote conservation.

Three experimental treatments are used that parallel water management options that an urban water manager may adopt to promote water conservation. Varying group size simulates water management at the local, neighborhood level and at the larger, city-wide level. Provision of information about users' decisions is analogous to a manager informing residents of water use within their neighborhood or water use across the city. The communication treatment is similar to a community newsletter or city-wide bill insert depending on group size.

I find that a large group size with no communication produces the least conservation. Participants choose to consume as much as they can prior to the consumption of another, however, this result may be sensitive to the single-stage framework. A small group size with communication produces the most coordinated behavior. Results show that information plays a role in the player decision, however, the impact varies by treatment. Information in a large group with no communication tends to stabilize player decisions. In that setting communication increases the amount of water privately consumed. In the small group treatment, consumption increases when information is present without communication but decreases with communication. I use the Wilcoxon, non-parametric method to test the hypothesis that each of the treatments impact the participants' consumption decision. The null is rejected in each case.

The results suggest urban water policy implications for managers. First, experiment participants conserved more in the small group size. This suggests that a neighborhood approach to conservation may produce better results than at the city-wide level. Second, information about the water use decision of other participants impacts individual consumption. In the large group size it tends to increase consumption and in small groups in tends to decrease consumption. This strengthens the argument for approaching conservation at a neighborhood level over city-wide. Third, the participants' consumption is less in the presence of communication. Together, these three results imply that a community organized approach to conservation may be more effective than city-wide encouragement to conserve.

There are a series of extensions that will increase the information on the individual conservation decision. The first is to econometrically estimate the impact of socio-demographic and conservation preferences that are in the survey data. This will allow for generalization of the sample results to the larger population and take a closer look at how these impact community organization and the likelihood of increased conservation. Based on the information found here, in another series of experiments I would like to investigate conservation as a social norm to see how information and group expectations impact the decision.

Increased water scarcity implies that sustainable management practices are of increasing need. The results in this paper suggest that a community organized approach to water conservation may be a useful, non-price, demand-side management planning tool. Public good benefits that accrue to users outside of the urban system can influence the customer decision if customers know about them and collectively engage in a coordinated effort. Thus, a community organized approach to conservation is another tool in the water manager's arsenal of effective water policies.

Chapter 5

Concluding Remarks

Urban water managers face two primary concerns; failing infrastructure and increasing scarcity. As the U.S. water infrastructure continues to age, and as long as managers can successfully prevent disruptions to consumers, dealing with infrastructure repair and replacement will be an issue left at the level of the local utility. Federal assistance is linked to voter interest; managers that successfully minimize service interruptions suppress voter outcry. This means that utility managers will have to find ways to address infrastructure issues from within. At the same time, increased water scarcity means that managers will have to get customers to use less water or face deleterious consequences. The three papers in this dissertation address components of these two urban water policy concerns. The first paper focused on optimal water infrastructure investment. The second paper identified optimal pumping, efficient water prices, and simulated utility profits that could be used to address infrastructure issues. The third paper considered a non-price, demand-side policy option for promoting conservation.

The sum of water infrastructure investment shortfalls at the utility level across the U.S. are estimated at \$23 billion annually (WIN, 2000a). The water utility data from the AWWA that I use suggests that the average U.S. water utility that serves in excess of 50,000 people faces a \$21 million annual shortfall. Over 20 years, estimated need reaches as much as \$2.2 trillion (WIN, 2000b). Infrastructure investment gaps are a multi-year, multi-billion dollar problem. Compounding the problem is that water delivery is a silent service, people are not generally concerned about water infrastructure until they are personally impacted. In aggregate, this implies that federal response may not be adequate until the level of service disruptions nationwide elicit voter response. Consequently, dealing with infrastructure shortages is a problem largely left to water utility managers.

The model in Chapter 2 offers a tool water resource managers can use to mitigate investment shortfalls. In an optimal control theory framework, using an adjustment cost model, I model the path of optimal infrastructure investment. The model reveals three important considerations. The effects of population, system capacity, and policy impact the investment path, which suggests that the manager can shift policy towards optimal investment by considering these. Thus, the model serves as a guideline since choosing investment optimally mitigates investment shortfalls.

The second policy concern is that water supplies are increasingly scarce. In order to avoid water shortages, people will need to use less. This, combined with the identified need for water infrastructure investment, motivates the "two-for-one" consideration that I analyze in Chapter 3. The question is: can a water resource manager solve water scarcity and infrastructure shortfalls by implementing scarcity prices? To answer this question, groundwater availability constrains the social welfare maximization model in an optimal control theory framework. The differential equation system that is the solution contains a path of optimal groundwater pumping, from it optimal water prices are identified. Optimal water prices occur where price equals the sum of marginal production cost and marginal user cost. The marginal user cost is the opportunity cost placed on all future water users for water that is used today.

Chapter 3 presents a comparison of simulation results from the optimal water use program and the status quo alternative, which I characterize as one where water prices increase at the rate of inflation. Over a 40-year time horizon, using Albuquerque, New Mexico as a test case, I consider impacts to the height of the water table, society, and the financial impact to the water provider. The results indicate that current water prices are approximately 20 percent of the price level that includes the marginal user cost, the level that signals water scarcity. The optimal price path preserves 21.6 feet of water table height over the alternative. The results shed light on the importance of modifying current regulatory pricing barriers. Optimal water pricing preserves aquifer height, generates revenue for capital investment, and reduces monthly water use at the individual level thus promoting conservation.

Increased water scarcity suggests that entities who compete for this finite resource will have to make-do with less. For the urban dweller, this implies water conservation; for the urban water manager, this implies finding ways to promote conservation. Chapter 4 considers a non-price, demand-side management alternative to investigate water conservation. Conserved water is an impure public good since it is non-excludable and rival in consumption. These features mean that it is susceptible to free-riding behavior by water users. The water user-group may know that overall, everyone needs to use less water but individually may not be inclined to do so. This dichotomy between private and public interests is labeled collective versus individual rationality in the literature (Budescu et al., 1995). The experimental application in Chapter 4 considers three possible ways to overcome that dichotomy.

The three experimental treatments that I implement, group size, information, and communication, parallel management policies a manager may adopt. Group size sheds light on the level, neighborhood or city-wide, at which conservation should be promoted. Information provides insight as to how water consumption of others impact one's own water use. Communication shows how a coordinated effort may reduce water use. The results suggest that a small group size with communication decrease consumer water consumption. The impact of information is mixed and varies with group size. In a small group setting the presence of information causes consumption decisions to decline and converge. In a large group it increases consumption decisions. The highest level of individual consumption occurs in a large group. These results suggest that an organized, neighborhood approach to water conservation is more successful at reducing consumption than city-wide encouragement.

There are a series of extensions to this dissertation that will continue to broaden the understanding of efficient urban policy in the context of drought and economic uncertainties. The model of optimal water infrastructure investment is at the level of the utility and general infrastructure. First, an extension to the investment model that disaggregates infrastructure will shed light on how the effects of population, aging capital, and policy impact specific infrastructure types. It may be the case that the impacts from these three effects are not the same across transmission mains, pumping systems, or treatment facilities. Second, the optimal pumping model relies on certain groundwater recharge. Extending it to make recharge stochastic and modeling surface water as part of available supply will provide useful insights on optimal water use, especially in times of drought. Estimating the cost function as a trans-log will pick up groundwater, well-specific effects. Third, econometrically estimating the consumer water decision with experimental treatment variables and survey data will provide for greater characterization of consumption versus conservation. Finally, in another experiment, conservation could be modeled as a social norm to investigate how this impacts the consumption decision of new users to the water system.

The three papers in this dissertation collectively speak to water utility, financial stability and water sustainability. The models inform policy makers of factors that promote optimal infrastructure investment, groundwater pumping, and conservation. The findings here are consequential since water managers can use them on the path to more efficient water management. Extending this research will continue to find ways to deal with financing and replacing infrastructure, arriving at optimal water use, and making water conservation a social norm.

Appendices

Appendix A

Econometric Model of Optimal Investment

Transforming theory model (2.20) and (2.21) into econometric model (2.22) and (2.23) to derive estimators in Table 2.2

$$\dot{m} = \frac{[pf_k - c] + [(\delta + \eta + r)(pf_m - g)] - [pf_{mk}(m - (\eta + \delta)k)]}{pf_{mm}}. \tag{A.20}$$

Substituting in $r = \eta - \rho$ then distributing terms yields:

$$\dot{m} = \frac{pf_k - c + (\delta + 2\eta - \rho)pf_m - (\delta + 2\eta - \rho)g - pf_{mk}\dot{k}}{pf_{mm}}.$$

Divide through by denominator then gather terms according to data variables (var): c, g, p, m, and k. Thus model equation (2.20) becomes regression equation (2.22).

$$\dot{m} = \underset{\beta_0}{\frac{f_k + (\delta + 2\eta - \rho)f_m}{f_{mm}}} \quad \underset{\beta_1}{-\frac{1}{f_{mm}}} \quad \underset{\text{var}}{\frac{c}{p}} \quad \underset{\beta_2}{-\frac{(\delta + 2\eta - \rho)}{f_{mm}}} \quad \underset{\text{var}}{\frac{g}{p}} \quad \underset{\beta_3}{-\frac{f_{mk}}{f_{mm}}} \quad \underset{\text{var}}{\dot{k}}$$

$$\Delta m_i = \beta_0 + \beta_1 \frac{c_{it}}{p_{it}} + \beta_2 \frac{g_{it}}{p_{it}} + \beta_3 \Delta k_i + \gamma_i \mathbf{z}_{ij} + \epsilon_1 \tag{A.22}$$

The second part of the model is

$$\dot{k} = m - (\delta + \eta)k. \tag{A.21}$$

The econometric version of (2.21) becomes econometric equation (2.23).

$$\begin{array}{cccccc} \dot{k} = & 0 & +1 & m & -(\delta+\eta) & k \\ & \alpha_0 & \alpha_1 & \text{var} & \alpha_2 & \text{var} \end{array}$$

$$\Delta k_i = \alpha_0 + \alpha_1 m_{it} + \alpha_2 k_{it} + \gamma_i \mathbf{z}_{ij} + \epsilon_2. \tag{A.23}$$

Appendix B

Experiment Protocol Treatments

B.1 Small Group – No Communication

Welcome to this experiment on water use decision-making. Thank you for participating. We expect that this experiment will take approximately one hour.

This experiment will consist of several separate rounds. Your group will start each round with 34 water units in your "Public Water Bucket." During each round you might choose to take some water from the "Public Water Bucket" and place it in your "Private Water Bucket" or you may choose not to take any.

In each round you will be in a group of three people. We will not tell you who the other members of your group are, and we will not tell any other participants whether or not you are in their group. The members of your group will remain the same throughout the experiment; therefore you will be in the same group of three participants for all rounds.

Your earnings for the experiment are based on the amount of water in your "Private Water Bucket" and remaining water in the "Public Water Bucket." You may place any amount of water in your "Private Water Bucket" that you wish in whole amounts (i.e. no fractions). However, if the total water demand of your group exceeds that which is available in the "Public Water Bucket," each member of your group receives a prorated portion of the privately desired amount to put in their "Private Water Bucket."

Remaining water in the "Public Bucket" increases by a factor of two and each person in your group gets an equal share. This means that the trick is to decide how much water to put in your "Private Bucket" so that you earn as much money as you can.

[DISTRIBUTE THREE HANDOUTS NOW]

The handouts "Returns from the Public Water Bucket" and "Returns from the Private Water Bucket" show you how remaining water and water convert to earnings expressed in dollars. At the end of each round, the experimenters will record water you get to put in your "Private Water Bucket," your groups remaining water in the "Public Water Bucket," and your payment for that round. For your records, you may record the same information on the "Decision and Earnings" handout. That is, you will record the water you get to keep and the associated earnings under "Your Decision." Under "Group Decision" you will record water remaining in the "Public Water Bucket" and the associated earnings. You will add the private and public earnings [columns (a) and (b)] to see the amount you earned on that round.

However, we will not pay you for every round. The bingo cage will contain one number for each round you play. For example, if we complete five rounds, numbers one through five will be placed in this bingo cage. The numbers I draw from the cage will determine the rounds for which you will be paid. Since each number has an equal chance of being drawn, you should play each round as if it is a round that will count towards your payment. We will draw two rounds and add your total earnings from each round to determine your payment.

Here is how you will complete the first round of this experiment:

Your group has 34 water units in the "Public Water Bucket". You determine the amount you would like to place in your "Private Water Bucket." There is a chance that the total demand of your group exceeds 34. If it does, we will prorate the individually desired amount and let you know how many water units you get to keep.

Here is how we prorate when water demand exceeds water supply:

First we determine the total water demand for your group by adding the individual decisions. Then we divide the available supply 34, by the total demand to get a ratio. We multiply that ratio by your individual decision and that is how much you get to keep.

That sounds like a lot of math: dont worry. We will calculate that for you and let you know how much of your desired water you get to keep.

Here is an example of how this works:

If each person in your group demands 15 water units, total demand is 45, which is greater than the available 34 units. The experimenter prorates the amount that each player gets to keep and reports to you that you get 11 water units. You look at your "Returns from the Private Water Bucket" handout and if, for example, it said that 11 units earn you $14 dollars your "Private Bucket Earnings" would be $14. One unit remains in the "Public Water Bucket." That earns you and each participant in your group $1 dollar. Thus, your total earnings for this hypothetical round would be $15 dollars.

Here is another example:

If each person in your group demands zero water units, total demand is zero and 34 water units remain in the "Public Water Bucket." You look at the "Returns from the Public Water Bucket" handout to see that 34 units earn $23 for each participant in your group. That means that for this hypothetical round you would earn zero dollars from your "Private Water Bucket" and $23 from the groups "Public Water Bucket" so that $23 would be your total earnings and the total earnings of each player in your group.

Does anyone have any questions about this part of the experiment?

Remember:

You may choose any number of water units that you like for your "Private Water Bucket."

The number of water units that you get to keep depends on total water demand and water supply.

Please write your ID number, shown on your "Decision and Earnings" handout, on the form the experimenters are handing to you.

Please do not talk or communicate with any other participant. Please do not look at the paperwork of other players and please keep all your paperwork and decisions private. A folder has been provided for you to enclose your paperwork at the end of each round.

After you have made your decision, please fold your decision sheet in half, write your ID# on the outside of the sheet, and hand it to one of the assistants.

This concludes Round 5. Please write your ID# on the outside of your folded Round form. Once all Round forms have been gathered, the experimenters will determine the water units you get to keep in your Private Water Bucket and the remaining water units in the Public Water Bucket and return the form to you.

Round 6, and each remaining round of this experiment will be different.

At the conclusion of this round, we will enter your Private Bucket decision onto a chart on the decision round sheet of your group members.

The chart will display the Private Bucket decision of each participant in your group although individual participants will remain anonymous. You will not know who the other participants in your group are; you will only know the amount that they requested from the Public Water Bucket. Your decision will also be displayed anonymously; your group members will not know your identity.

The only participant information you will know will be your own since your decision will correspond to one of the participants on the chart.

Now please make your Round 6 decision.

B.2 Large Group – No Communication

Welcome to this experiment on water use decision-making. Thank you for participating. We expect that this experiment will take approximately one hour.

This experiment will consist of several separate rounds. Your group will start each round with 136 water units in your "Public Water Bucket." During each round you might choose to take some water from the "Public Water Bucket" and place it in your "Private Water Bucket" or you may choose not to take any.

Your earnings for the experiment are based on the amount of water in your "Private Water Bucket" and remaining water in the "Public Water Bucket." You may place any amount of water in your "Private Water Bucket" that you wish in whole amounts (i.e. no fractions). However, if the total water demand of your group exceeds that which is available in the "Public Water Bucket," each member of your group receives a prorated portion of the privately desired amount to put in their Private Water

Bucket.

Remaining water in the "Public Bucket" increases by a factor of two and each person in your group gets an equal share. This means that the trick is to decide how much water to put in your "Private Bucket" so that you earn as much money as you can.

[DISTRIBUTE THREE HANDOUTS NOW]

The handouts "Returns from the Public Water Bucket" and "Returns from the Private Water Bucket" show you how remaining water and water convert to earnings expressed in dollars. You will record on the "Decision and Earnings" handout three pieces of important information. You will record the water you get to keep and the associated earnings under "Your Decision." Under Group Decision you will record water remaining in the "Public Water Bucket" and the associated earnings. You will add the private and public earnings [columns (a) and (b)] to see the amount you earned on that round.

However, we will not pay you for every round. The bingo cage will contain one number for each round you play. For example, if we complete five rounds, numbers one through five will be placed in this bingo cage. The numbers I draw from the cage will determine the rounds for which you will be paid. Since each number has an equal chance of being drawn, you should play each round as if it is a round that will count towards your payment. We will draw two rounds and add your total earnings from each round to determine your payment.

Here is how you will complete the first round of this experiment:

Your group has 136 water units in the "Public Water Bucket." You determine the amount you would like to place in your "Private Water Bucket." There is a chance that the total demand of your group exceeds 136. If it does, we will prorate the individually desired amount and let you know how many water units you get to keep.

Here is how we prorate when water demand exceeds water supply:

First we determine the total water demand for your group by adding the individual decisions. Then we divide the available supply 136, by the total demand to get a ratio. We multiply that ratio by your individual decision and that is how much you get to keep.

That sounds like a lot of math: dont worry. We will calculate that for you and let you know how many of your desired water units you get to keep.

Here is an example of how this works:

If each person in your group demands 15 water units, total demand is 180, which is greater than the available 136 units. The experimenter prorates the amount that each player gets to keep and reports to you that you get 11 water units. You look at your "Returns from the Private Water Bucket" handout and if, for example, it said that 11 units earn you $14 dollars your "Private Bucket Earnings" would be $14. Four units remain in the "Public Water Bucket" that earn you and each participant in your group $1 dollar. Thus, your total earnings for this hypothetical round would be $15 dollars.

Here is another example:

If each person in your group demands zero water units, total demand is zero and 136 water units remain in the "Public Water Bucket." You look at the "Returns from the Public Water Bucket" handout to see that 136 units earn $23 for each participant in your group. That means that for this hypothetical round you would earn zero dollars from your Private Water Bucket and $23 from the groups "Public Water Bucket" so that $23 would be your total earnings and the total earnings of each player in your group.

Does anyone have any questions about this part of the experiment? Remember:

You may choose any number of water units that you like for your "Private Water Bucket."

The number of water units that you get to keep depends on total water demand and water supply.

Please write your ID number, shown on your "Decision and Earnings" handout, on the form the experimenters are handing to you.

Please do not talk or communicate with any other participant. Please do not look at the paperwork of other players and please keep all your paperwork and decisions private. A folder has been provided for you to enclose your paperwork at the end of each round.

Please fold your decision sheet in half, write your ID# on the outside of the sheet, and hand it to one of the assistants.

B.3 Small Group – Communication

Welcome to this experiment on water use decision-making. Thank you for participating. We expect that this experiment will take approximately one hour.

This experiment will consist of several separate rounds. Your group will start each round with 34 water units in your "Public Water Bucket." During each round you might choose to take some water from the "Public Water Bucket" and place it in your "Private Water Bucket" or you may choose not to take any.

In each round you will be in a group of three people. We will not tell you who the other members of your group are, and we will not tell any other participants whether or not you are in their group. The members of your group will remain the same throughout the experiment; therefore you will be in the same group of three participants for all rounds.

Your earnings for the experiment are based on the amount of water in your "Private Water Bucket" and remaining water in the "Public Water Bucket." You may place any amount of water in your "Private Water Bucket" that you wish in whole amounts (i.e. no fractions). However, if the total water demand of your group exceeds that which is available in the "Public Water Bucket," each member of your group receives a prorated portion of the privately desired amount to put in their "Private Water Bucket."

Remaining water in the "Public Bucket" increases by a factor of two and each person in your group gets an equal share. This means that the trick is to decide how much water to put in your "Private Bucket" so that you earn as much money as you can.

[DISTRIBUTE THREE HANDOUTS NOW]

The handouts "Returns from the Public Water Bucket" and "Returns from the Private Water Bucket" show you how remaining water and water convert to earnings expressed in dollars. At the end of each round, the experimenters will record water you get to put in your "Private Water Bucket," your groups remaining water in the "Public Water Bucket," and your payment for that round. For your records, you may record the same information on the "Decision and Earnings" handout. That is, you will record the water you get to keep and the associated earnings under "Your Decision." Under "Group Decision" you will record water remaining in the "Public Water Bucket" and the associated earnings. You will add the private and public earnings [columns (a) and (b)] to see the amount you earned on that round.

However, we will not pay you for every round. The bingo cage will contain one number for each round you play. For example, if we complete five rounds, numbers one through five will be placed in this bingo cage. The numbers I draw from the cage will determine the rounds for which you will be paid. Since each number has an equal chance of being drawn, you should play each round as if it is a round that will count towards your payment. We will draw two rounds and add your total earnings from each round to determine your payment.

Here is how you will complete the first round of this experiment:

Your group has 34 water units in the "Public Water Bucket." You determine the amount you would like to place in your "Private Water Bucket." There is a chance that the total demand of your group exceeds 34. If it does, we will prorate the individually desired amount and let you know how many water units you get to keep.

[DISTRIBUTE DISCUSSION BOARD SHEET TO GROUPS]

Before you decide how much water you would like to place in your "Private Water Bucket" you may write on the "Discussion Board" one or two sentences that you would like for the your group members to read. The "Discussion Board" for each round is in your folder. Please write legibly so your group can read your comments.

We will photo copy your comments onto a single "Discussion Board" sheet that only you and your group members will see. Each group will have their own "Discussion Board." Only you will know which comments belong to you, all comments will remain anonymous.

Here is how we prorate when water demand exceeds water supply:

First we determine the total water demand for your group by adding the individual decisions. Then we divide the available supply 34, by the total demand to get a ratio. We multiply that ratio by your individual decision and that is how much you get to keep.

That sounds like a lot of math: dont worry. We will calculate that for you and let you know how much of your desired water you get to keep.

Here is an example of how this works:

If each person in your group demands 15 water units, total demand is 45, which is greater than the available 34 units. The experimenter prorates the amount that each player gets to keep and reports to you that you get 11 water units. You look at your "Returns from the Private Water Bucket" handout and if, for example, it said that 11 units earn you $14 dollars your "Private Bucket Earnings" would be $14. One unit remains in the "Public Water Bucket." That earns you and each participant in your group $1 dollar. Thus, your total earnings for this hypothetical round would be $15 dollars.

Here is another example:

If each person in your group demands zero water units, total demand is zero and 34 water units remain in the "Public Water Bucket." You look at the "Returns from the Public Water Bucket" handout to see that 34 units earn $23 for each participant in your group. That means that for this hypothetical round you would earn zero dollars from your "Private Water Bucket" and $23 from the groups "Public Water Bucket" so that $23 would be your total earnings and the total earnings of each player in your group.

Does anyone have any questions about this part of the experiment? Remember:

The assistants are handing you your groups Round 1 "Discussion Board." Please read the comments and make your water decision.

You may choose any number of water units that you like for your "Private Water Bucket."

The number of water units that you get to keep depends on total water demand and water supply.

Please write your ID number, shown on your "Decision and Earnings" handout, on the form the experimenters are handing to you.

Please do not talk or communicate with any other participant. Please do not look at the paperwork of other players and please keep all your paperwork and decisions private. A folder has been provided for you to enclose your paperwork at the end of each round.

After you have made your decision, please write any comments you would like to make for the Round 2 "Discussion Board."

Please fold your decision sheet in half, write your ID# on the outside of the sheet, and hand it to one of the assistants.

B.4 Large Group – Communication

Welcome to this experiment on water use decision-making. Thank you for participating. We expect that this experiment will take approximately one hour.

This experiment will consist of several separate rounds. Your group will start each round with 136 water units in your "Public Water Bucket." During each round you might choose to take some water from the "Public Water Bucket" and place it in your "Private Water Bucket" or you may choose not to take any.

Your earnings for the experiment are based on the amount of water in your "Private Water Bucket" and remaining water in the "Public Water Bucket." You may place any amount of water in your "Private Water Bucket" that you wish in whole amounts (i.e. no fractions). However, if the total water demand of your group exceeds that which is available in the "Public Water Bucket," each member of your group receives a prorated portion of the privately desired amount to put in their Private Water Bucket.

Remaining water in the “Public Bucket” increases by a factor of two and each person in your group gets an equal share. This means that the trick is to decide how much water to put in your “Private Bucket” so that you earn as much money as you can.

[DISTRIBUTE THREE HANDOUTS NOW]

The handouts “Returns from the Public Water Bucket” and “Returns from the Private Water Bucket” show you how remaining water and water convert to earnings expressed in dollars. You will record on the “Decision and Earnings” handout three pieces of important information. You will record the water you get to keep and the associated earnings under “Your Decision.” Under Group Decision you will record water remaining in the “Public Water Bucket” and the associated earnings. You will add the private and public earnings [columns (a) and (b)] to see the amount you earned on that round.

However, we will not pay you for every round. The bingo cage will contain one number for each round you play. For example, if we complete five rounds, numbers one through five will be placed in this bingo cage. The numbers I draw from the cage will determine the rounds for which you will be paid. Since each number has an equal chance of being drawn, you should play each round as if it is a round that will count towards your payment. We will draw two rounds and add your total earnings from each round to determine your payment.

Here is how you will complete the first round of this experiment:

Your group has 136 water units in the “Public Water Bucket.” You determine the amount you would like to place in your “Private Water Bucket.” There is a chance that the total demand of your group exceeds 136. If it does, we will prorate the individually desired amount and let you know how many water units you get to keep.

[DISTRIBUTE DISCUSSION BOARD SHEET TO GROUPS]

Before you decide how much water you would like to place in your “Private Water Bucket” you may write on the “Discussion Board” one or two sentences that you would like for the your group members to read. The “Discussion Board” for each round is in your folder. Please write legibly so your group can read your comments.

We will photo copy your comments onto a single “Discussion Board” sheet that only you and your group members will see. Each group will have their own “Discussion Board.” Only you will know which comments belong to you, all comments will remain anonymous.

Here is how we prorate when water demand exceeds water supply:

First we determine the total water demand for your group by adding the individual decisions. Then we divide the available supply 136, by the total demand to get a ratio. We multiply that ratio by your individual decision and that is how much you get to keep.

That sounds like a lot of math: dont worry. We will calculate that for you and let you know how many of your desired water units you get to keep.

Here is an example of how this works:

If each person in your group demands 15 water units, total demand is 180, which is greater than the available 136 units. The experimenter prorates the amount that each player gets to keep and reports to you that you get 11 water units. You look at your “Returns from the Private Water Bucket” handout and if, for example, it said that 11 units earn you \$14 dollars your “Private Bucket Earnings” would be \$14. Four units remain in the “Public Water Bucket” that earn you and each participant in your group \$1 dollar. Thus, your total earnings for this hypothetical round would be \$15 dollars.

Here is another example:

If each person in your group demands zero water units, total demand is zero and 136 water units remain in the "Public Water Bucket." You look at the "Returns from the Public Water Bucket" handout to see that 136 units earn $23 for each participant in your group. That means that for this hypothetical round you would earn zero dollars from your Private Water Bucket and $23 from the groups "Public Water Bucket" so that $23 would be your total earnings and the total earnings of each player in your group.

Does anyone have any questions about this part of the experiment? Remember:

You may choose any number of water units that you like for your "Private Water Bucket."

The number of water units that you get to keep depends on total water demand and water supply.

Please write your ID number, shown on your "Decision and Earnings" handout, on the form the experimenters are handing to you.

Please do not talk or communicate with any other participant. Please do not look at the paperwork of other players and please keep all your paperwork and decisions private. A folder has been provided for you to enclose your paperwork at the end of each round.

Please fold your decision sheet in half, write your ID# on the outside of the sheet, and hand it to one of the assistants.

Appendix C

Experiment Protocol Handouts

Figure C.1: Decision and Earnings Handout

GROUP
5

KEEP THIS SHEET PRIVATE

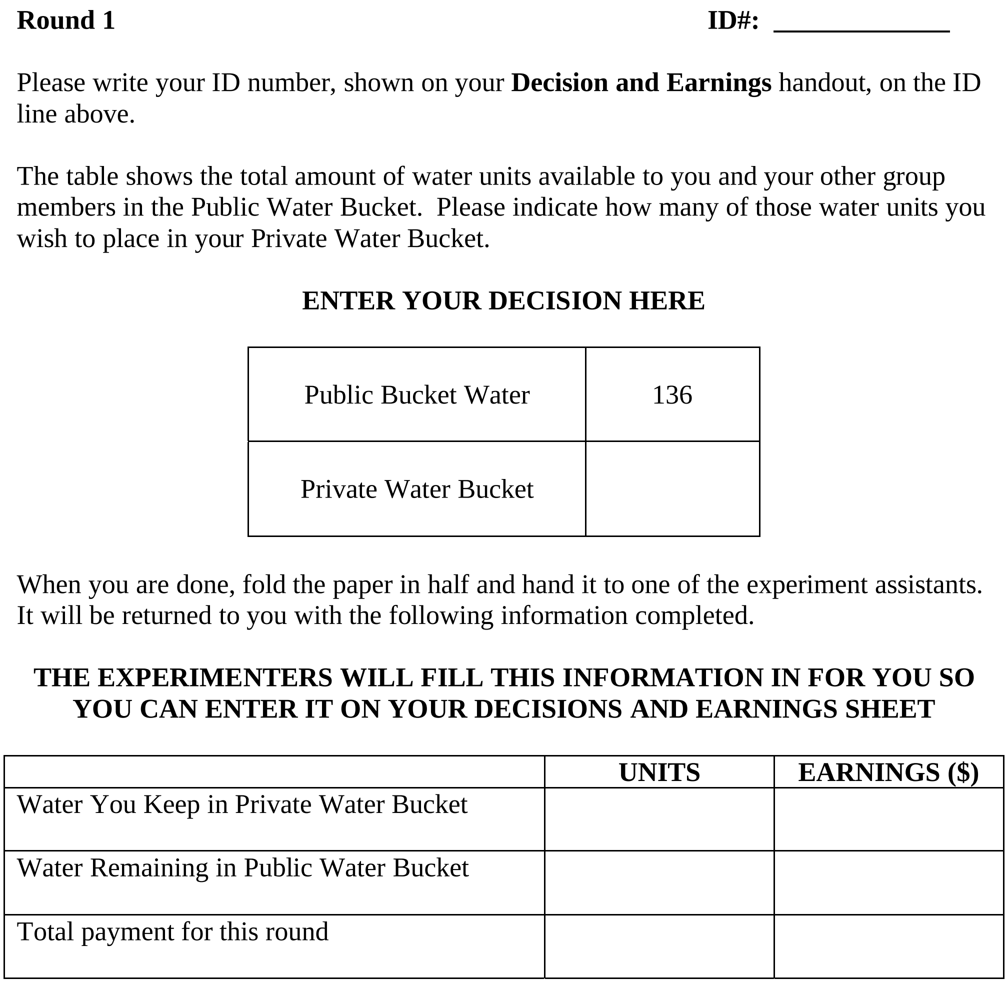
ID#
52301

Decision and Earnings Sheet

	Your Decision		Group Decision		
Round	Water You Keep	Private Bucket Earnings (a)	Water Remaining	Public Bucket Earnings (b)	Total Earnings (a) + (b)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					

Payment made on rounds ____________ and ____________

Figure C.2: Decision Round Sheet Large Group



Round 1 **ID#:** ____________

Please write your ID number, shown on your **Decision and Earnings** handout, on the ID line above.

The table shows the total amount of water units available to you and your other group members in the Public Water Bucket. Please indicate how many of those water units you wish to place in your Private Water Bucket.

ENTER YOUR DECISION HERE

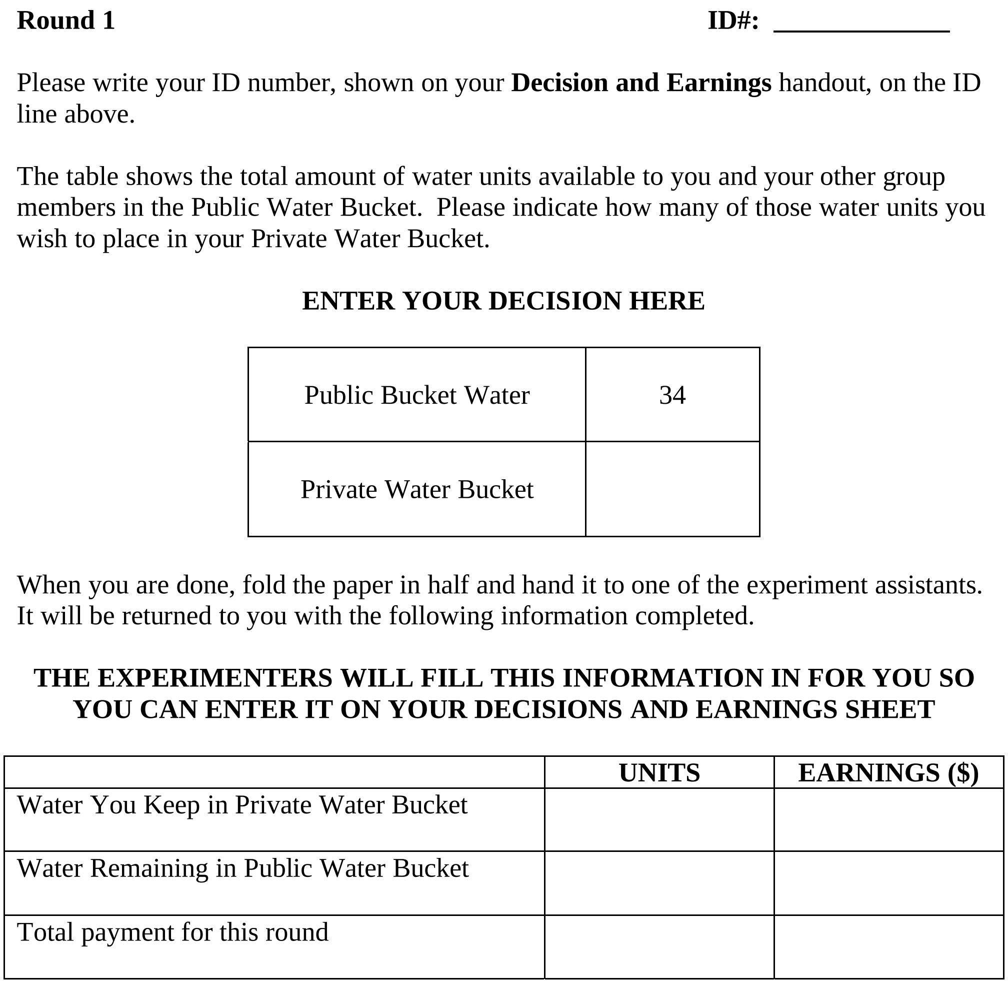
Public Bucket Water	136
Private Water Bucket	

When you are done, fold the paper in half and hand it to one of the experiment assistants. It will be returned to you with the following information completed.

THE EXPERIMENTERS WILL FILL THIS INFORMATION IN FOR YOU SO YOU CAN ENTER IT ON YOUR DECISIONS AND EARNINGS SHEET

	UNITS	**EARNINGS ($)**
Water You Keep in Private Water Bucket		
Water Remaining in Public Water Bucket		
Total payment for this round		

Figure C.3: Decision Round Sheet Small Group – No Information



Round 1 **ID#: _____________**

Please write your ID number, shown on your **Decision and Earnings** handout, on the ID line above.

The table shows the total amount of water units available to you and your other group members in the Public Water Bucket. Please indicate how many of those water units you wish to place in your Private Water Bucket.

ENTER YOUR DECISION HERE

Public Bucket Water	34
Private Water Bucket	

When you are done, fold the paper in half and hand it to one of the experiment assistants. It will be returned to you with the following information completed.

THE EXPERIMENTERS WILL FILL THIS INFORMATION IN FOR YOU SO YOU CAN ENTER IT ON YOUR DECISIONS AND EARNINGS SHEET

	UNITS	**EARNINGS ($)**
Water You Keep in Private Water Bucket		
Water Remaining in Public Water Bucket		
Total payment for this round		

Figure C.4: Decision Round Sheet Small Group – Information

Round 6 **ID#:** ____________

Please write your ID number, shown on your **Decision and Earnings** handout, on the ID line above.

The table shows the total amount of water units available to you and your other group members in the Public Water Bucket. Please indicate how many of those water units you wish to place in your Private Water Bucket.

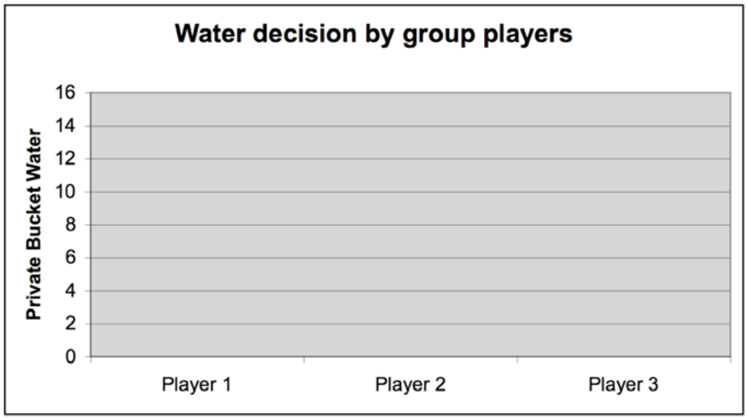
ENTER YOUR DECISION HERE

Public Bucket Water	34
Private Water Bucket	

When you are done, fold the paper in half and hand it to one of the experiment assistants. It will be returned to you with the following information completed.

THE EXPERIMENTERS WILL FILL THIS INFORMATION IN FOR YOU SO YOU CAN ENTER IT ON YOUR DECISIONS AND EARNINGS SHEET

	UNITS	**EARNINGS ($)**
Water You Keep in Private Water Bucket		
Water Remaining in Public Water Bucket		
Total payment for this round		



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